Improving Highways Construction Processes using Computer-based Simulation techniques.

PhD Candidate: Rana Muhammad Qasim

Student ID: @00278932

Supervised by: Dr Zeeshan Aziz

School of Built Environment
University of Salford
Greater Manchester

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Declaration

The author declares that this thesis is the outcome of his own work. No portion of this work has been submitted in support of an application for another degree or qualification at this or any other university or institution of higher learning. However, some of the material has been published by the author in peer-reviewed journal articles and conference papers which is explicitly mentioned and acknowledged in the thesis. The journal/conference papers are attached in Appendix 4 and 5.

Publications

The Author has published the following during the research, which constitutes outputs produced part of this research.

Papers

Aziz, Z., Qasim, R.M. & Wajdi, S., 2017. Improving the productivity of road surfacing operations using value stream mapping and discrete event simulation. *Construction Innovation*, 29(1), pp.1–6. Available at: http://www.emeraldinsight.com/doi/full/10.1108/CI-11-2016-0058 .

Qasim, R.M., Aziz, Z. & Alfar, E., 2017. Enhancing resurfacing operations with the integration of Lean and Discrete Event Simulation. *Engineering, Construction and Architectural Management*, (Special Issue on Lean and BIM). Submitted 5th December 2017.

Qasim, R.M. & Aziz, Z., 2017. Improving Productivity of Road Surfacing operations with the help of Lean and Discrete Event Simulation techniques; a UK case study. *The 9th International Conference on Construction in the 21st Century (CITC-9) March 2017*. Dubai, UAE: ASCE Journal of Professional Issues in Engineering Education and Practice.

Qasim, R.M. & Aziz, Z., 2017. Improving Road Surfacing Operations by Using Value Stream Mapping and Simulation techniques. *The International Postgraduate Research Conference*. Salford, UK: University of Salford. Available at: http://conference.org.uk/international-research-week/. Submitted 5th June 2017.

Reports

Aziz, Z, Qasim, R.M., & Alfar, E., 2017. *Increasing Efficiency of Earthmoving & Pavement Processes at Highways England*, Manchester. Available at: https://kol.withbc.com/pub/english.cgi/d379427192/A3 KTP - Earthworks.pdf.

Abbreviations

CAD	Computer-aided Diagrams
CRA	Constructive Research Approach
DES	Discrete Event Simulation
DFT	Department for Transport
DRIVE	Define-Review-Identify-Verify-Execute
DS	Design Science
DSR	Design Science Research
GDP	Gross Domestic Product
GPSS	General Purpose Simulation System
HE	Highways England
PDCA	Plan-Do-Check-Act
S.D	System Dynamics
SRN	Strategic Road Network
TM	Traffic Management
TQM	Total Quality Management
UK	United Kingdom
USA	The United States of America
VSM	Value Stream Mapping

Abstract

Roads are long-term infrastructure investments and are a valuable asset to the community. While it is crucial to construct new roads for various societal functions, maintaining the existing ones is also essential to develop a safe and accessible road network. Road construction projects suffer from tight schedules, massive traffic volumes, low budgets and environmental constraints that affect the productivity of road construction. Road sector is quite fragmented, and various companies are involved in a construction process. Most of these businesses have their internal procedures that are usually different from other stakeholders, which make it more complicated to improve a particular process. This research aimed to improve highways construction processes at the activity level by using the integration of manual and computer-based simulation tools.

This research involved simulating two different as-is process highways related operations to experiment different what-if scenarios that are not possible otherwise to try in real life. It also involved investigating the underutilisation of simulation techniques in the highway sector. The case studies chosen for this project were resurfacing (maintenance) and earthworks (construction) operations. This integration of simulation and lean boosted the output of various highways maintenance and construction operations and maximised the efficiency of resources involved. The data was collected from reports, on-site observations and constant collaboration with the industry partners.

This research succeeded in developing two artefacts (two detailed, lean-integrated simulation models) which were based on real projects and were verified and validated by the experts from highways and simulation backgrounds. It involved using Design Science or Constructive research methodology to identify an industry based problem, study it in detail and then develop a practical solution which can be implemented by industry to solve this issue. The developed models are based on two particular case studies; however, they are designed in such a way that they can be easily modified according to the needs and conditions of different countries and similar projects. There are thousands of simulation models available online but lack the ability and freedom to change accordingly and do not have detailed guidelines about its construction, usage and adjustments.

The developed models have practical applications in highways and other construction organisations for planning and execution stages. Stakeholders that can benefit from this research are developers, contractors, transport departments, highways agencies, resurfacing companies, highways maintenance contractors and most importantly the general motorists. Drivers will benefit from facing reduced repair works and minimum disruption to traffic caused by highways agencies and sub-contractors. Construction management students will also reap the outcomes of this research as the integration of lean and discrete event simulation has not frequently been discussed in the construction management context and is still a new concept.

A significant knowledge gap exists regarding improvement of construction processes. Existing optimisation approaches are based on manual procedures, are fragmented and not making the best use of computer-aided methods to improve operations. As the industry is becoming more competitive, there is a need to enhance various construction (decision making and ground level) activities that can ultimately improve the efficiency for overall construction projects. Current improvement approaches mostly involve manual procedures like Value Stream Mapping, DRIVE (Define-Review-Identify-Verify-Execute), PDCA (Plan-Do-Check-Act) and process mapping etc. These processes can further be enhanced by using a computer-based environment to experiment different what-if situations. The demand for enhancement can be fulfilled by utilising computer-based simulation methods that have already proven its ability in manufacturing, process and production industries.

This research contributes to the existing body of knowledge by adapting constructive research methodology or design science method for developing a practical solution to improve highways/construction processes. The research is based on two real-life case studies, and all data collection is being done within the structure of case studies. These projects are first studied in detail, and then different experimental scenarios are performed to improve the as-is processes. This research was based on two different sorts of highways operations (resurfacing and earthworks), and the findings are limited to these two operations only. Even though these operations are the most frequent and important ones, there are many other processes which can also be studied and improved in the same manner. At the same time, the models created in this research are designed not to be very project-specific and can be used in projects of a similar nature.

Chapter 1 : Introduction to the Research

Sections

1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
Introduction	Problem Statement	Justification of using Simulation	Research Questions	Aims and Objectives	Research Method	Scope of Research	Research Limitations	Summary of Chapters

This chapter presents background information to define the purpose of this research. It discusses some background about the problem, presents problem statement, explains how it can be solved, provides justification of problem-solving method and lists the aims and objectives of the research. This chapter delivers the significance and need of this research work along with the explanation about the type of approaches used. At the end of this section, a summary of each following chapter is included to guide the reader in a stepwise manner.

1.1 Introduction

Transportation has a significant role in the socio-economic growth of a region (Rodrigue, Comtois and Slack, 2016). It has various modes to travel from one point to another, i.e. highways, railways, airways and waterways. All these forms of transportation serve different purposes and are essential in modern-day life. Railways, Airways and waterways typically travel from one point to another. However, they require further door to door highways network to transport goods, where needed. This intensifies the significance of road network in modern life (Maji and Jha, 2009).

Road network is critical in urban life, and it is intricately connected with social, economic and environmental issues (Taylor, 2008). An efficient road network requires constant maintenance for best possible results; however, rapidly increasing traffic has made it hard for maintenance activities to be performed (Department for Transport UK, 2011; Kolosz & Grant-Muller 2015). More significant traffic volume has resulted in abridged road space for maintenance and servicing activities (ODT, 2014). Continuously increasing traffic and other disturbances on the road cause congestion resulting in delayed journeys, queuing, bottlenecks, accidents and negative feedback from users and this difficulty has been on the rise since the last three decades (Jones, 2011). Many solutions have been tested to mitigate the problem including infrastructure developments, better planning and improvements in vehicles. However, the least focus is directed towards enhancing the current maintenance and construction procedures to meet society's demand. A key challenge is to deliver major road schemes in resource-constrained environments while maintaining safety, cost efficiency, sustainability and minimal impact on road users (Department for Transport UK, 2013).

The road sector faces many difficulties including pushing demands like quicker, economic and efficient production, construction, resurfacing and maintenance (Rehborn *et al.*, 2011; Aziz, Qasim and Wajdi, 2017). To decrease the interruption of roads for maintenance and construction activities, it is vital to upgrade the traditional style of working. Due to rapidly increasing traffic, time slots available for development, reparation and rehabilitation projects are becoming tighter and tighter, implying that maintenance techniques have to be speeded up (Christory et al., 2008). Another challenge with current working styles is the productivity deficiency in the construction sector.

The variation in productivity has been defined as the quantity difference between "planned to be completed" and "actually completed" in a given period (Ballard and Howell, 1998). There is ample room for enhancement in efficiency of road work projects within the construction industry to achieve maximum competence, smooth traffic flow, and a lesser amount of waste and minimal traffic disruption. Municipal infrastructure schemes represent substantial public investments and are supposed to be accomplished using most well-organized practices (Burningham and Stankevich, 2005). Productivity enhancement in various construction operations can save billions of dollars each year, and it has been proven at multiple times (Pande, Neuman and Cavanagh, 2000).

Productivity improvement is a hot topic in academic literature as well as business research. The reason is the reduced performance, schedule and cost overruns and lack of efficacy in the construction sector (Changali et al., 2015). It is important to improve the construction sector due to its significant and leading role in the economy of a country. Governments keep trialling new rules and procurement policies to upsurge overall output and lessen waste in industry practices. However, satisfactory results are never obtained in improving the construction operations performance due to many reasons (Kenley, 2014).

Construction performance has been declining recently as compared to manufacturing or service-based industries. There are numerous reasons behind the reduced performance that vary from country to country (Green, 2016). Some of the main issues impacting the productivity are related to climate, equipment, the general economy, quality, culture and work methods (Botero et al., 2004). The factors that directly affect the performance of labour are associated with management and administration activities. In maintenance projects, efficiency is the measurement of the effectiveness with which resources are utilised to deliver the project within the prescribed time and given quality standards (Dozzi and AbouRizk, 1993). The scope of efficiency and productivity is comprehensive, so the major focus should be on increasing the particular process's efficiency. In this case, effectiveness in the road sector is investigated.

This research aims to improve highways construction and maintenance processes at activity level by using the integration of Discrete Event Simulation (DES) and lean strategy. It seeks to simulate the as-is process to experiment different what-if scenarios that are not possible otherwise to try in real life. This integration of DES and lean will boost the output of various highways maintenance operations and maximise the efficiency of resources involved.

1.2 Problem Statement

Existing highways construction and maintenance processes are marred with fragmentation and productivity losses. This research intends to solve an industry-related problem, i.e. optimisation of highways construction and maintenance operations that has a potential to contribute to theory as well. After thoroughly reviewing the literature and by meeting relevant stakeholders, it was realised that there are productivity related issues in the construction sector as a whole and highways sector in particular (Department for Transport UK, 2011, 2013; Mostafavi *et al.*, 2012; Green, 2016; Inman, 2016). It was further noticed that computer-based simulation techniques are not utilised up to their full potential in highways sector, and a substantial amount of savings can be made by using it at various stages in a project (Marzouk, Fouad and El-said, 2011).

The construction industry is a significant factor for most of the economies as it can influence the country's gross domestic product (GDP) and can also be affected by it (Madi, 2003; Hughes and Thorpe, 2014). The construction industry has been a crucial element in the robust growth of almost every economy around the world (Raftery *et al.*, 1998). It is critical to maximising the efficiency of the construction sector as it contributes about 7% of the UK's GDP and the sector is worth around £110 Billion per year. (Office of National

Statistics 2010). It comprises of commercial (£49bn), residential (£42bn) and infrastructure (£18bn) projects. Furthermore, the refurbishing and improving existing infrastructure costs about half of this total (Cabinet Office 2011). Therefore, it is crucial that the construction process in the UK works efficiently and has the least wastage. According to Anne Francke, the chief executive of the Chartered Management Institute, Poor management of resources and excessive waste costs the UK economy £84 billion a year (Haughton, 2017).

According to the recent report on construction efficiency published by (Changali et al., 2015), 98% of the total projects incurred delays or cost overruns; where the average increased cost was 80% of actual value and the average time delay was 20 months. Construction productivity has been on a decline for decades whereas the manufacturing industry has nearly doubled during the same period. The United Kingdom is about 20% less productive than its competitors, and it has been the same for a few years. It was said by Gordon Brown in his pre-budget report about 20 years ago (Graham Ruddick, 2016).

Accurately measuring the productivity is a challenging task to accomplish given due to the nature of production in the industry and because the data is not readily available (Sveikauskas *et al.*, 2014). However, one can still focus on what is available and try to improve it as much as possible. Then this developed version can be replicated and lessons learnt from manufacturing, production and healthcare sectors can be implemented in the construction industry as well.

In highways sector, most of the infrastructure (roads) is similar to each other, and its construction and maintenance are performed in a standard way practised throughout the world (Aziz, Qasim and Wajdi, 2017). Here, manufacturing and production principles can be applied, and a massive amount of waste can be eliminated.

Figure 1.1 below displays the GDP per hour productivity of various developed countries and the UK scores much lower than Germany, the United States, France and even Italy (Inman, 2016). When the demand is rising, the production process has to be speeded up and improved to satisfy the needs. Similarly, the number of road users is on the rise and roads will be deteriorating at a much faster pace (ODT, 2014).

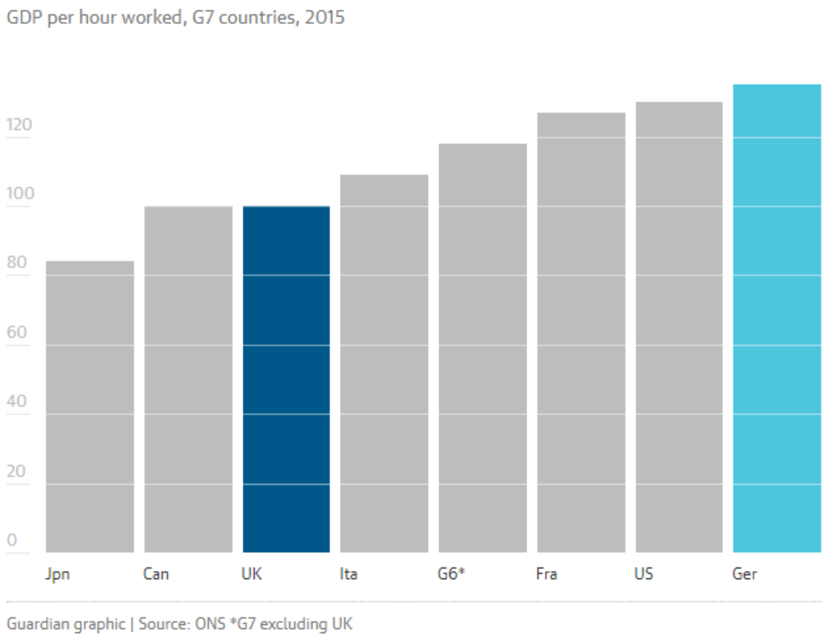


Figure 1.1 GDP per hour productivity in different countries (Inman, 2016)

The construction and maintenance of the road network are becoming critical in these times of physically collapsing infrastructure (World Bank, 2011). The price of such projects is continuously increasing and to stay competitive, building operations have to be as productive as possible (Gowda, Singh and Connolly, 1998). Small or medium-sized contractors and firms do not/can not spend much on research and process optimisation efforts. Large contractors (Tier 1 and Tier 2) only rely on manual techniques like lean, process mapping and TQM (Total Quality Management), etc. Simulation techniques can act as an economical solution for process improvement studies that can assist in increasing the efficiency of construction operations. Simulation is the reflection or imitation of a real-world operation or a system (Banks *et al.*, 2010). Simulation modelling is one of the many modern techniques to solve real-world problems by creating a context within which the situation can be investigated (Law and Kelton, 2000).

Highways context is unique when compared to other industries like manufacturing or processing because of its fragmented nature which requires a more in-depth approach (Dutta et al., 1993; National Research Council, 1994). The business consists of various engineering companies, contractors, suppliers, and equipment manufacturers and equipment providers (BIS, 2013). Since different stakeholders are involved in the construction and maintenance of highways at different tier levels, various improvement schemes are frequently overlooked due to deficiency of consensus between stakeholders. This was also acknowledged by the Office of the Parliamentary Counsel, (2013) that having more stakeholders in any project makes it complicated, and the improvement schemes are often ignored. However, if there is an improvement plan with firm evidence, e.g. a simulation model and it manages to take all stakeholders on board, there is less room for rejection.

Experts like Detty and Yingling, (2000a), Schroer, (2004) and Marvel and Standridge, (2009) have discussed the integration of lean and simulation for validation of lean and understanding it in detail. Abdulmalek and Rajgopal, (2007), Miller and Pawloski and Standridge, (2010) have successfully implemented this combination in the manufacturing sector. Stewart Robinson *et al.* (2012) and Baril *et al.*, (2016) have tested this in the healthcare sector effectively. This research work, however, has used this combination of lean and discrete event simulation on an operation level in the highways maintenance and construction processes which is different from the works carried out earlier.

For this purpose, the contemporary literature related to highways and resurfacing has been reviewed, but no application of a computer-aided improvement program that can assist in decision-making and overall process improvement was noticed. There is a need to address this gap by undertaking applied research in highways case studies and will strive not only to improve their as-is processes but also contribute to the process optimisation theory in construction

1.3 Justification for using Computer Based Simulation Techniques

Process enhancement performs a critical role in the success of organisations. Its fundamental purpose is to improve the business by determining, examining and modifying any process within the firm to achieve maximum optimisation (Williams, 2017). It should involve a systematic approach which uses a particular methodology, but the paths within it may change. Process optimisation can include a series of actions to achieve new goals and objectives like reducing waste, lessening costs, maximising profits and improving overall performance (Ciribini, Mastrolembo Ventura and Paneroni, 2016). It is usually possible when a particular methodology or technique is adopted which has been proven beneficial previously (Breyfogle, 2014).

It is necessary to understand the process first in in-depth detail to improve any particular process, various techniques and methodologies require an individual to investigate, analyse and then develop any activity to gain maximum productivity. It also involves the experts of this area, and their commitment assures the success of this endeavour (Oakland, 2003). Different techniques have different standards and implications, and their relevance also varies from industry to industry. There are various methodologies used for the purpose of process optimisation, and some of them are very popular and useful like Six Sigma, Lean, and TQM methodology (Williams, 2017). There are many other tools as well as Pareto Analysis, Statistical Process Control (SPC) and brainstorming, etc. All these techniques are manual based and are do not have a comprehensive solution to issues that are hidden currently and may arise in the future.

Existing approaches to process innovation are manual based and do not optimally utilise new opportunities available like process simulation. These manual based methods do not remove the uncertainty and ambiguity in the projects and have limited power to predict the future events with evidence. Simulation techniques have proven their strengths in various fields like **Healthcare** (Gaba, 2007; Rosen *et al.*, 2008; Ahmed and Alkhamis, 2009; Chahal and Eldabi, 2011; Stewart Robinson *et al.*, 2012; Xie and Qingjin Peng, 2012; Basole, Bodner and Rouse, 2013; Bennett and Hauser, 2013; O'Regan, 2014; Scerbo, 2016), **Manufacturing** (Miller and Pegden, 2000; Mcdonald and Aken, 2002; Fowler, 2004; Lian and Van Landeghem, 2007; Banks *et al.*, 2010; Jahangirian *et al.*, 2010; Miller, Pawloski and Standridge, 2010; AbouRizk *et al.*, 2011; Lee, Han and Yang, 2011; Seleim, Azab and AlGeddawy, 2012; Negahban and Smith, 2014), **Processing** (Abdulmalek and Rajgopal, 2007; Seth, Seth and Goel, 2008) and **Construction** (Martinez and Tech, 1998; El-Haik and Al-Aomar, 2006; Huang, Bird and Bell, 2009; Yu *et al.*, 2009; Gurumurthy and Kodali, 2011; Jarkko *et al.*, 2013; Labban *et al.*, 2013; Alterawi, 2014; Qasim, Aziz and Alfar, 2017b), etc. The author has reviewed the literature thoroughly, interacted with industry experts in person and used his own experiences to come up with a conclusion that existing approaches are manual and have limitations.

Computer-based simulation modelling techniques have been utilised in highways maintenance sector by some researchers like Marzouk et al. (2011), Lee & Ibbs (2005) and Gowda et al. (1998). However, their scope of the study was insufficient. They emphasised one essential activity within a process and tried to improve it. The implications of the simulation are wide ranged and comprehensive. The idea of simulation modelling is to map all the small activates within a model and then try to improve each individual activity and the overall process as well. This will ensure maximum productivity on an operation scale and will also provide a holistic view of the process, before and after the improvements.

Simulation techniques are not fully utilised to its maximum potential (Paltved *et al.*, 2017), and same is the case with Highways sector. There are many operations like resurfacing, paving and traffic management which is repeated each night throughout the country in exactly the same manner. There are no significant changes except weather and road layouts etc. and the overall process stays the same. In these circumstances, a process should be mapped in detail; it should be improved as much as possible (within the safety limits) and then replicated afterwards on all schemes (Dahl and Minken, 2008). This can save billions of pounds of public money each year, and it has been demonstrated in the case study chapter as well.

In the UK and other countries around the world, many manual approaches are utilised for process optimisation purposes since the 1970s. The fundamental objective of all of them is to maximise the productivity and reduce any waste in the operations of various industries. Some of the critical methodologies are discussed here in detail to explain their applications and limitations, which will justify the use of simulation that is utilised in this research work. Table 1 below displays various process improvement methods and compare their strengths. It can be noticed that apart from simulation techniques, most of them perform in a similar manner and have the same functions. However, it has little particular strength that cannot be carried out by other, manual approaches like Lean and Six Sigma.

Table 1-1 Comparative analysis of various process improvement approaches

Technique Abilities	Lean	Six Sigma	TQM	Discrete Event Simulation	Other Techniques DRIVE, PDCA cycles, Brainstorming
In-depth Understanding of Process	X (Bertelsen and Koskela, 2004; Hicks, 2007)	X (Koning and Mast, 2006; Kwak and Anbari, 2006; Tjahjono *et al.*, 2010)	X (Sadegh, Alireza and Behzad, 2013; Talib, 2013)	X (Bernard J. Schroer, 2004; Borshchev and Filippov, 2004; Matloff, 2008)	X (Hickethier *et al.*, 2011; Prashar, 2017)
Visualising complex processes in 3D				X (Chen and Huang, 2013; Oyekan *et al.*, 2015)	
Performance Measurement	X (Marlow and Casaca, 2003; Bhasin, 2008; Fullerton and Wempe, 2009)	X (Coronado and Antony, 2002; Raisinghani *et al.*, 2005; Kwak and Anbari, 2006)	X (Powell, 1995; Kumar *et al.*, 2008; Agus and Hassan, 2011)	X (Günal and Pidd, 2010; Cigolini *et al.*, 2014; Bohez *et al.*, 2015; Aziz, Qasim and Wajdi, 2017)	X (Gunasekaran, Patel and McGaughey, 2004)
Capture	X (Shah and Ward, 2003; Womack, Jones and Jones, Daniel; Womack, 2003; El-Haik and	X (Tjahjono *et al.*, 2010)	X (Aoieong, Tang and Ahmed, 2002; Soare, 2012)	X (Aziz, Qasim and Wajdi, 2017; Schriber, Brunner and Smith, 2018)	

	Al-Aomar, 2006)				
What-if scenarios testing				X (Dombrowski and Ernst, 2013; Golzarpoor *et al.*, 2013)	
Evidence-based future planning.				X (Hoot *et al.*, 2008; Schacter, Addis and Buckner, 2008; Dombrowski and Ernst, 2013)	
Reduce Uncertainty				X (Duguay and Chetouane, 2007; Parks *et al.*, 2011; Nourinejad and Roorda, 2014)	

There are numerous other process enhancing tools, techniques and methodologies that have evolved over time and are utilised in various sectors throughout the world. Most of the times, one method or apparatus is not comprehensive enough and has to be integrated with other tools or approaches to gain the desired results. Most of them have the same purpose but differ in their working style, objectives and procedures. There are pros and cons to all of them, and much of the literature can be written about it. However, this study justifies the need for Simulation after discussing these techniques briefly.

1.4 Research Questions

There are a few research questions which will be answered during this research journey. It is necessary to define these questions before commencing the actual research as they will steer the focus of the study and will ensure that the researcher is not driving away from the research track. The questions are:

1. What are the productivity-related challenges faced by the highways sector, specifically UK roads sector?
2. What are the gaps in productivity in the maintenance and construction of highways and what improvements are needed in the industry?
3. What are the current practices of process optimisation and what are their limitations?
4. Is there any need for a computer-based process improvement approach?
5. How can the existing construction and maintenance processes be improved with discrete event simulation tools.
6. Are there any relationships between discrete event simulation and lean methodologies?
7. How can this integration benefit the construction sector?
8. If a solution is developed for the aforementioned issues, how its credibility will be justified?
9. Will the developed artefact (solution) be applicable to other similar scenarios as well or will it be project specific?

1.5 Aims and Objectives

The aim of

To achieve this aim, the following objectives are set to be accomplished:

1. To generate an understanding of productivity challenges in highways/construction sector in the United Kingdom.
2. To evaluate the need for computer-based improvement paradigms in construction and specifically highways operations.
3. To explore the synergy between various manual and computer-based process optimisation methodologies and integrate them for enhanced benefits.
4. To undertake pilot projects involving simulation techniques in two of the real life highways projects.
5. To validate the findings of the pilot projects by focus groups with industry experts.

1.6 Methodological Steps

This study has been divided into 5 stages to understand the journey in a stepwise manner. The first part of this research is knowledge acquisition which deals with literature review about the highways sector and finding relevant data about the optimisation theories in practice. It will demonstrate the challenges faced by the highways sector; current problems faced the construction industry in terms of productivity, and manual-based improvement techniques and then finally computer-aided simulation methods. This will set the theme and demonstrate the need for using such approaches and how they can prove beneficial in the highways sector around the world. The results of this section will help in presenting a summary of the current situation and the requirements of future.

The second stage is called formalisations stage where two separate pilot projects are performed using Highways England's projects in the UK. Figure 1.2 below shows the key 5 steps in the research journey and how they will be completed using specific research methods and techniques. It also explains the stages of the investigation, what tools will be used to collect the relevant data and what will be the outcomes. The literature review and industry interactions are based on action research approach where the researcher works in close collaboration with industry participants to understand the problem in detail and then jump for the solution stage.

The third stage is systemization and testing. In this step, a conceptual model is created which then leads to actual model creation after verifications. After that, simulation modelling will be used to simulate the as-is situation of two different operations (resurfacing and earthworks). After modelling, various tests can be performed in the computer environment to find the best scenarios and then the results are verified and validated by demonstrating to experts and make any suggested modifications in the model. Validation is the 4th stage of research.

Lastly, the fourth stage is validation and refinement where a researcher arranges interviews, workshops, focus groups to verify and validate the findings of his or her research and gather feedback on the working of artefact and how it can be improved.

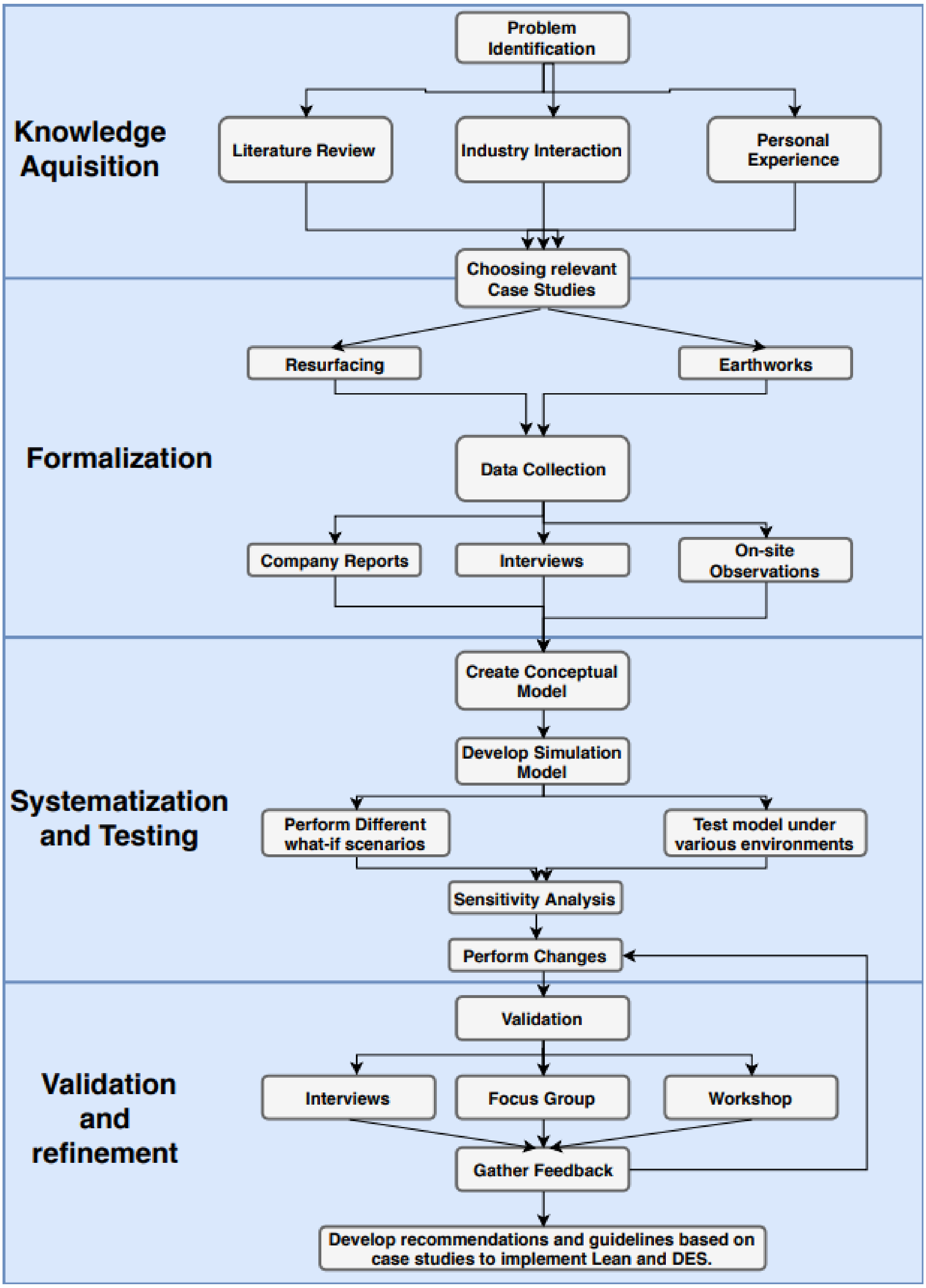


Figure 1.2 5 stages of this research work.

A journal article will also be published using each case study to demonstrate the findings and the contribution to theory. It will also act as blinded peer-reviewed feedback on the work performed and its results. Finally, during implementation and documentation stage, the researcher will develop a set of recommendations in each case to improve these two processes. Figure 1.3 below shows how the objectives of this research will be achieved using various research methods and techniques in step by step manner. It is similar to the 5 stages explained briefly at the beginning of this section.

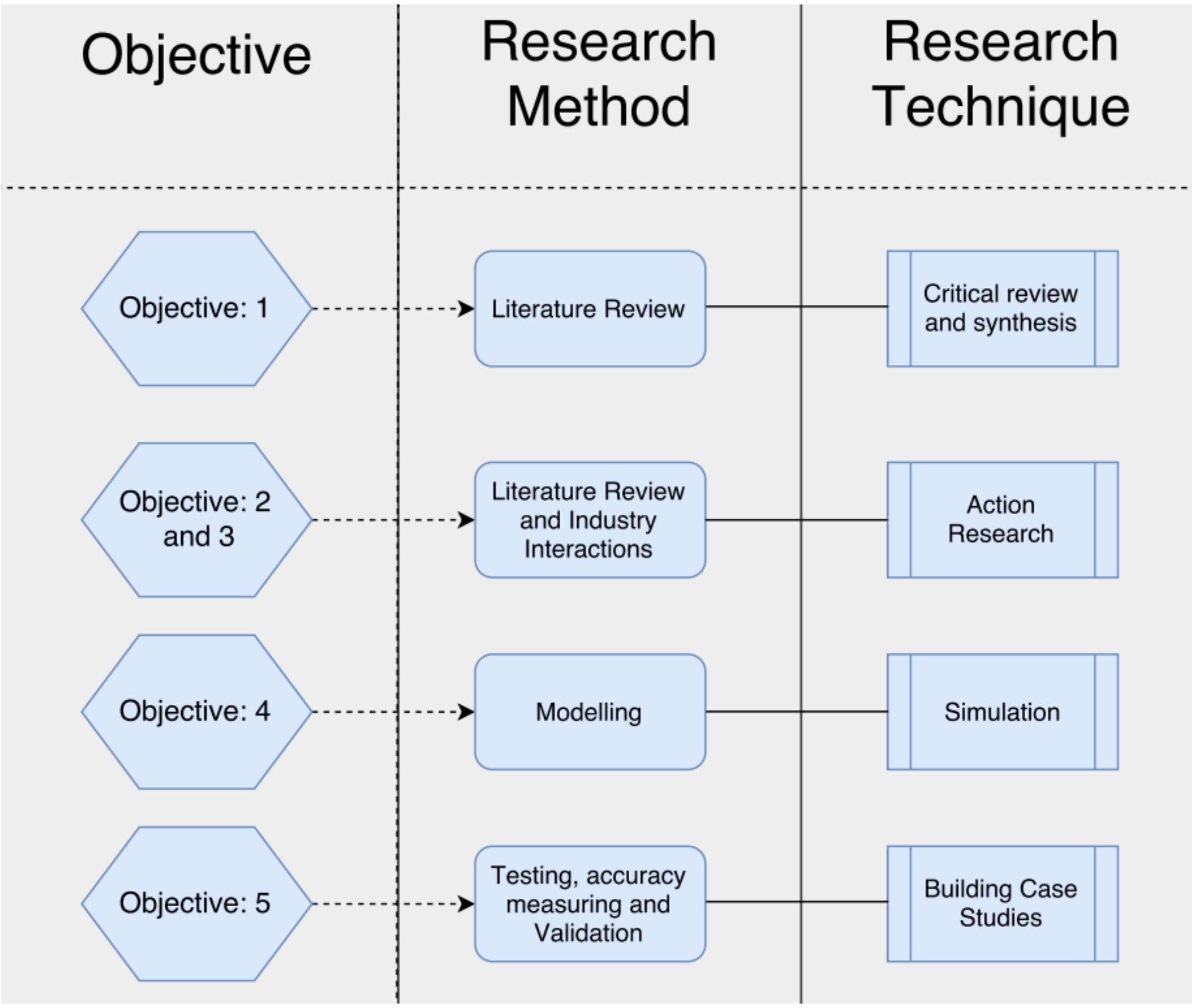


Figure 1.3 Research steps and how they will be achieved.

1.7 Research Contributions

The data obtained from the literature review and industry interactions show that the demand for process optimisation in the construction sector is increasing. Various improvement methods are being adopted, and now there are particular job positions as lean managers and development manager, etc. Simulation techniques are not being utilised to their maximum potential within the construction and especially within the highways sector.

The implications of this research are twofold. First, it studied, observed and simulated the as-is highways construction processes to improve it. Secondly, it encompassed most relevant stakeholders at validation stage to verify and validate the proposed results. It not only helped in getting feedback from various stakeholders but also provided a holistic view of the productivity-related issues on operation level that can be further added to the simulation models. Highways sector is very fragmented, and this effort will strive to create a construct/artefact which can be accepted by most stakeholders involved.

The purpose of this investigation was to reduce the waste in the construction and highways maintenance procedures that are regularly carried out throughout the year. A substantial amount of savings can be made using this combination of lean and simulation to improve the process by planning, enhancing and executing it efficiently. Stakeholders that can benefit from this research are contractors, transport departments, highways agencies, resurfacing companies, highways maintenance contractors and most importantly the general motorists. Drivers will benefit from facing reduced repair works and minimum disruption to traffic caused by highways agencies. Construction management students will also reap the outcomes of this research as the integration of lean manufacturing, and discrete event simulation is not a commonly discussed topic.

Experts like Detty and Yingling, (2000a), Schroer, (2004) and Marvel and Standridge, (2009) have discussed the integration of lean and simulation for validation of lean and understanding it in detail. Abdulmalek and Rajgopal, (2007) Miller and Pawloski and Standridge, (2010) have successfully implemented this combination in the manufacturing sector. Stewart Robinson *et al.* (2012) and Baril *et al.*, (2016) have tested this in the healthcare sector effectively. This research work, however, has used this combination of lean and discrete event simulation on an operation level in the highways maintenance and construction processes which is different from the works carried out earlier.

The case studies for pilot projects were located in the United Kingdom and were managed by Highways England and their partners, and most of the primary data was provided by their company reports and from personal interactions between the researcher and experts. Although the study is performed in the UK, the implications are worldwide as the highways processes are similar in rest of the world, and they face similar challenges in productivity on operation level.

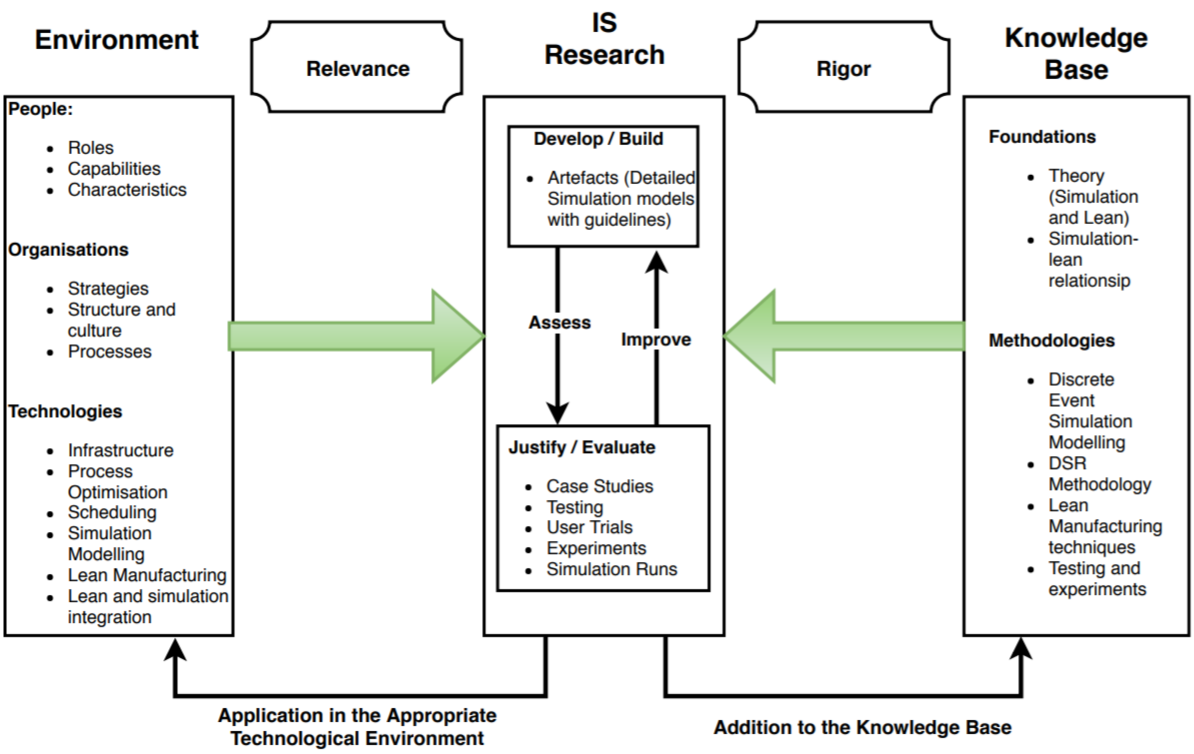


Figure 1.4 Research Contribution for knowledge contributions Hevner et al. (2004).

Figure 1.4 above, adopted from Hevner *et al.*, (2004) demonstrates the contribution of this research to the knowledge base and industry. During this research, the researcher developed expert skills in lean methodology, simulation modelling and discrete event simulation modelling, optimisation theories and project planning. The simulation models will help various organisations and its employees to plan the layout for resurfacing or earthworks operations effectively. End users, commuters will benefit as well when the disruption to traffic will be minimal and will increase road user satisfaction too.

The artefacts (two detailed simulation models along with guidelines) accurately enhance the productivity of two commonly practised construction processes and are easily implementable in any part of the world. Hevner *et al.*, (2004) and Hevner and Chatterjee, (2010) have stated that research must evidently address the contribution and solve a problem that was unsolved previously. This research work has successfully recognized a problem, i.e. low productivity in the construction described various improvement methods, chose a combination of two, developed a distinct and practical solution to solve it and then verified and validated it with the help of experts.

1.8 Research Limitations

The purpose of this research was to investigate the potential of simulation, lean manufacturing and their integration to enhance the productivity of highways and construction operations to minimise the waste of resources. Although the project has successfully developed and tested its simulation models on live projects (case studies) that demonstrated a considerable potential to improve cost and time savings and resource utilisations, it also has the following limitations:

- There are three paradigms of simulation modelling, i.e. Discrete Event Simulation (DES), Agent-Based Modelling and System Dynamics; however, due to insufficient time and other resources, this study has only investigated the implementation of DES paradigm.

- This investigation has contributed by developing two detailed simulation models based on two separate types of case studies, i.e. Resurfacing and Earthworks. However, construction and highways sector involves various other kinds of processes as well throughout the timeline of a project.

- The developed simulation models have only taken the operation stage of a project into consideration. The most significant justification for this step is that DES is most beneficial during the operation stages to experiment with various scenarios. It doesn't take in to account other stages of any construction process like decisions making, logistics or risk modelling etc.

- Simulation modelling has an enormous potential to improve resource utilisation and work plans; however, people may require extra training or courses to understand its working, methodology, experimentation tools and ability to understand the generated results. Many companies, especially SMEs are not willing to spend resources on training or adopting new technology which is a significant barrier.

- The data required for the simulation model development was collected within the United Kingdom, and these simulation models may not represent a generic picture of a resurfacing or construction process in other countries.

- During the development of simulation models, various factors like traffic conditions, logistics and the breakdown of vehicles etc. Were assumed to be under ideal situation without any significant trouble. This is a standard practice in simulation modelling to minimise the complexity of a model which will help in investigating an operation in in-depth detail.

- Although a simulation model can be integrated directly with lean manufacturing tools for enhanced planning and scheduling, however, it was done separately to avoid complexity and swaying from the scope of research.

- Real life data was captured and used for the development of models. However, synthetic data was used for testing and validation purposes at later stages due to unavailability of similar case studies in the limited timeframe.

1.9 Structure of Thesis

Chapter 1

Chapter 1 started with the introduction to highways and construction sector and set the theme of research. It begins by explaining the increasing demand for road space and how it is becoming scarce. This chapter presents the problem of productivity issues faced by the construction sector and especially the UK sector, and then briefly describe the current process improvement techniques and how simulation modelling can justify tackling these issues. It also explains research questions, aims and objectives to be achieved, research method to be used, the scope of work and finally the structure of the thesis.

Chapter 2

Chapter 2 presents the detailed section about literature review around the areas of challenges in the highways sector, UK's construction productivity gaps and Discrete Event Simulation (DES). It also explains current manual based approaches like Six-Sigma, Lean manufacturing, and Total Quality Management (TQM) etc. for process optimisation. Some of these techniques are described along with their sub-categories to fully understand their principle and how it can assist with the productivity-related issues. Finally, it talks about the combination of manual and computer-based methods used in this research, i.e. DES and Lean manufacturing.

Chapter 3

Chapter 3 presents the research design of a methodology section that is used in this thesis. It explains Constructive Research Approach or Design Science briefly about how it is different from traditional methods and how it helps in understanding the problem in detail. It starts with explaining the research philosophies, methodological considerations and the detailed process followed during design science research. It ends by describing how and why the developed "artefacts" will be verified and validated using analytical testing, and functional testing.

Chapter 4

Chapter 4 talks about the first case study or pilot project done for this research work. It is about the resurfacing operations that are performed all over the world for the maintenance of damaged roads. A UK case study is chosen, studied in detail and then modelled in Discrete Event Simulation paradigm. Lean manufacturing principles are applied to reduce wastage of resources and improve utilisation of machinery and working window etc. After modelling, different what-if scenarios were then performed to find the best practice, and the results are then validated and verified using theoretical testing, structural and functional testing and finally by focus group. Finally, recommendations to improve the current processes are made based on the findings of this pilot project.

Chapter 5

Chapter 5 displays the second case study about Earthworks. It is a fundamental step in most of the construction and involved a lot of heavy equipment and work. A UK case study has been chosen as a pilot project it has been modelled in a computer-based environment. After modelling, different scenarios are run that are not possible otherwise in real life. Lean manufacturing principles are applied to reduce wastage of resources and improve utilisation of machinery and working window etc. After modelling, different what-if scenarios were then performed to find the best practice, and the results are then validated and verified using theoretical testing, structural and functional testing and finally by focus group. Finally, recommendations are made to improve the earthworks process.

Chapter 6

Chapter 6 summarises the whole research work by presenting the main discussion and explaining how the objectives were successfully achieved in a step-by-step manner. It also includes the conclusion section which is actually the conclusion of the whole thesis. Finally, recommendations are made about how the research work can be utilised in real life and replicated in other scenarios.

Chapter 2 : Literature Review about Current Challenges in Construction, Highways and Process Improvement Techniques.

Sections

2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
Challenges faced by Highways England	UK's Construction Productivity; Gaps and Reasons.	Discrete Event Simulati on (DES)	Six Sigma	Lean Manufacturing	Total Quality management	Combinati on of Lean and DES	Comparing lean, six sigma and TQM

Literature review covers the predetermined research area by looking at the highways operations, efficiency-related issues, manual process improvement methods, simulation techniques, steps involved in it and its importance in construction and specifically highways sector. This section also explains current process improvement techniques like lean and Six Sigma and compares them with computer-aided simulation methods to elucidate the differences and shortcomings on either side.

2.1 Challenges faced by Highways Sector

Road networks have great importance in modern-day life. Highways England, which was previously known as Highways Agency from 1994 until April 2015, manages the Strategic Road Network (SRN) of England (Butcher, 2015). It is made up of 4,300 miles of road which although is only 2% of the road network in England. However, it carries one-third of all traffic flow in England (Hawksworth, 2014). Even though, more than 95% of England's residents use this network at least once a year, it has been suffering from historical under-investment. The forecasts suggest that the increase in traffic by 2040 can be 20 - 72% of this strategic road network and if there are no significant measures taken to upgrade it, UK economy will lose up to £10 billion a year by 2040 (Department for Transport UK, 2011).

Road space is becoming a scarce resource due to an ever-increasing number of private users. A study by INRIX and CBR (2014) estimated that between 2013 and 2030, the United Kingdom would pay the total accumulative cost of more than £300 Billion caused by congestion. This is equivalent to 18% of the UK's Gross Domestic Product (GDP) in 2013. This shows the ever-increasing demand for traffic management and roads up gradation. Last year in 2015, the government promised to upgrade the network to meet the needs of the 21st century by improving the quality of service, increase user's satisfaction, and support broader economic, safety and environmental goals.

The road network in England has suffered in recent years because of the lack of public sector investment, leading to adverse road user and economic impacts. UK Government has planned a long-term investment (2015-2020) of £11 billion of capital spend (DfT, 2016) to maintain, operate and improve 4300 miles of the strategic road network. The successful road network operation has the success of national and local economies and quality of life dependant on it. Thus, the focus of road network upgrades is beyond maintaining effective road surface, and Highways agencies are under pressure to address other performance indicators such as improving road user satisfaction levels, quality of service and support for the broader economy, safety and environmental goals.

Maintenance of current roads and constructing new roads never stops around the world. As the traffic increases, existing roads need expansion and up gradation. Due to large volumes of vehicles and frequent travels, existing roads lose their strength, aesthetic appearance, skid resistance and ride quality and require preservation and maintenance (Burningham and Stankevich, 2005).

There are various types of maintenance operations. However, the most common is called Resurfacing. It involves removing the top layer from the road, cleaning and pressing it with specialized vehicles and then putting a new asphalt surface on it. Highways England has fallen short of critical targets for road user satisfaction, according to results of the latest survey by the road and rail user watchdog Transport Focus.

2.2 UK's Construction Productivity; Gaps and Reasons.

Productiveness can be defined as the "ratio of outputs to inputs needed for delivery of yield in production". It is the "measure of output compared to the input" in the manufacturing industry. On the other side, productiveness in the construction sector can be described in different terms such as throughput rate, unit-person hour, performance factors, etc. (Dozzi and AbouRizk, 1993). Construction productivity was defined in detail by (Merrow et al., 2009) by using three approaches, i.e. economic approach, project approach and construction manager's approach. In the economic approach, labour efficiency related to per hour output is measured. In the project approach, the productiveness of the whole project is determined by comparing with previously established milestones.

Finally, the construction manager's technique assesses work performed per hour by individual or gang at any activity level to measure the efficiency. Productivity has two strong measures, i.e. use of labour and the relative ability of the workers to achieve the required task and the latter is more important to contractors and organised labour (Marzouk et al., 2011).

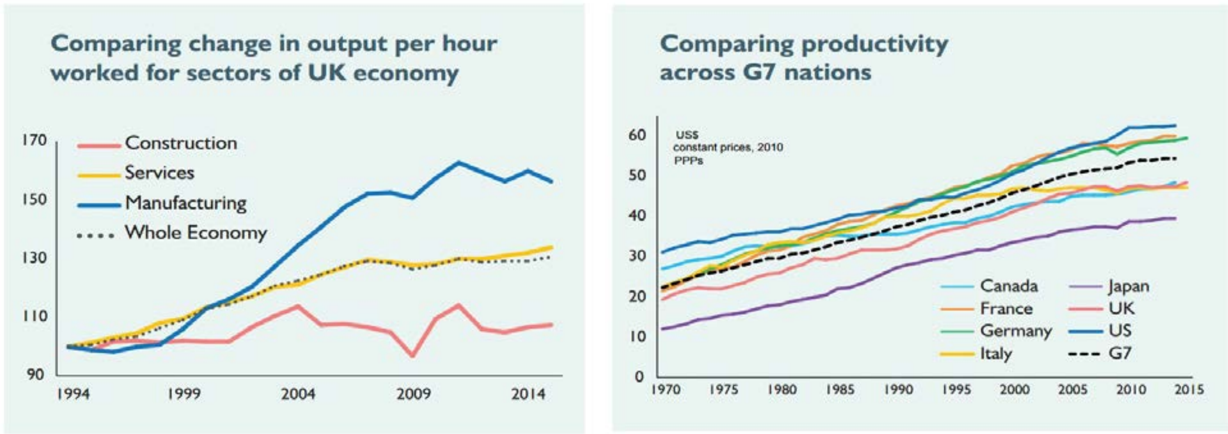


Figure 2.1 Comparison of Construction performance, Chartered Institute of Building UK.

Achieving maximum work rate is a significant issue in construction sector all over the world. It is a general perception that well-developed countries have more productive planning, workforce and delivery. However, Figure 2.1 above contradicts to this statement by showing the lousy performance of the United Kingdom in the construction sector during the last three decades compared to other G7 countries. Similar observations came from annual UK industry performance report (UKIPR, 2015) showing that the majority of construction projects were completed behind schedule in the UK.

A survey by the Construction Management Association of America (CMAA, 2005) showed that 40-50% of all construction projects failed to meet their time and cost targets in a developed country like the USA. This happened while the federal government implemented various productivity improvements in areas like planning, design, cost control, quality control, craft training, scheduling, safety and information technology (Picard, 2004).

According to the recent report on construction efficiency published by (Changali et al., 2015), 98% of the total projects incurred delays or cost overruns; where the average increased cost was 80% of actual value and the average time delay was 20 months. Construction productivity has been on a decline for decades whereas the manufacturing industry has nearly doubled during the same period. Figure 2.2 below demonstrates a glimpse of construction vs manufacturing sector efficiency in terms of value-added per worker.

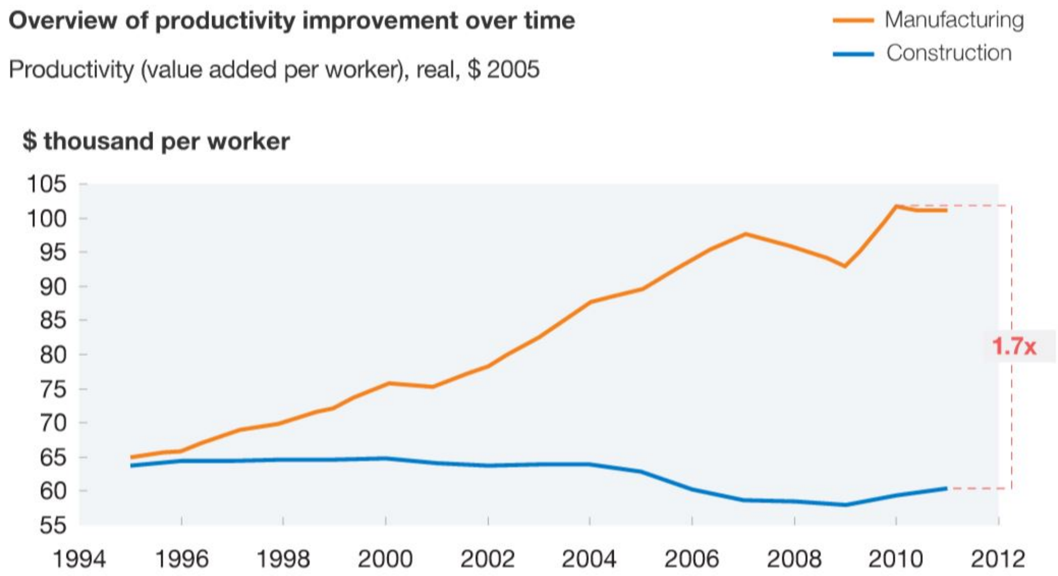


Figure 2.2: An overview of productivity improvement during last 2 decades, Changali et al. (2015).

Several factors need to be addressed in this area to increase the efficiency. Some of them are poor communication, poor organisation, contractual misunderstandings, weak short-termed planning, missed connections, limited talent management, flawed performance management and insufficient risk management (Green, 2016). If these issues are dealt with in a professional manner, straitened circumstances can be mitigated easily.

2.3 Discrete Event Simulation

Simulation is the reflection or imitation of a real-world operation or a system (Banks *et al.*, 2010). As a process evolves, its behaviour change with time and it can then only be studied in detail by creating a simulation model. This simulation model is developed using process-related information, relevant input data and some assumptions. This mixture of information is then presented using symbolic, mathematical and logical relationships between the objects or entities of that particular system (Flores, 2015). Robinson, (2005) has defined DES as:

"Discrete Event Simulation (DES) models the operation of a system as a separate sequence of events in time where each event occurs at a particular point in time and causes a change of state in the system. No change in the system is assumed to occur between consecutive events; thus the simulation can directly jump in time from one event to the next.”

Simulation modelling is one of the many modern techniques to solve real-world problems by creating a context within which the situation can be investigated (Law & Kelton, 2000). In various everyday cases, it is not feasible to experiment with real objects by building them from scratch, destroying them or making changes (Borshchev, 2014). It can be unsafe, expensive or sometimes not possible at all. Under these circumstances, a computer simulation model is created imitating the real situation, which can be experimented with at any level.

Construction simulation is a quickly developing area. It is the ability to create a model and then tests with these computer-based illustrations of construction operations to comprehend their principal behaviour (AbouRizk et al., 2011). After a model has been created, verified and validated, it can explain some what-if questions to remove ambiguity and uncertainty about future steps to a great extent. These questions cannot be answered by any other process mapping or improving technique like lean, six-sigma or TQM, etc.

Simulation allows to change or disrupt any operation in a computer-based environment and displays the impacts and results of such variations on the system (Law, 2007). This can prove useful in the planning and designing stage of any project before it is constructed. To summarise, simulation modelling can be employed as an analysis tool to predict consequences on any system and as a planning mechanism to forecast the functioning (Fishman, 2001).

Simulation modelling has been used in construction processes and is regarded as a reliable tool in project management (Gowda, Singh and Connolly, 1998). Engineers in a construction company can model any system or a process of any size to gain in-depth knowledge of the process and make it more efficient. Simulation modelling provides the operation planner with a medium for modelling real life and real-time processes and then running various what-if experiments in a computer-based environment.

Thousands of scenarios can be evaluated in a short amount of time which is not possible otherwise. On the other hand, simulation requires computer skills and knowledge about the modelling. Sometimes, the data collection process to create a simulation model can be expensive and tedious (Gowda, Singh and Connolly, 1998). It should be carefully decided whether simulation modelling is necessary for an individual process or not.

The implementation of simulation techniques in highways context is limited, and only a handful of studies have been done to advance the process, e.g. by (Maji & Jha, 2009; M Marzouk et al., 2011; Jones 2011). Existing optimisation approaches rely heavily on manual process methods like Process Activity Mapping, Quality Filter Mapping, Decision Point Analysis and Value Stream Mapping, etc. which have many limitations.

The implications of this research are twofold. First, it will study, observe and simulate the as-is highways processes to improve it. Secondly, it will encompass all relevant stakeholders at some stage to verify and validate the proposed results. Stakeholders that can benefit from this research are the transport departments, highways agencies, resurfacing companies, highways maintenance contractors and finally the general motorists.

Simulation modelling is a method to solve problems which occur in our real world. When the real-world problems are impossible or too expensive to experiment with, simulation models are made and investigated (Borshchev and Filippov, 2004). Modelling facilitates the process optimisation and implementation stages in various sectors. It starts by mapping the actual process using real-world activities and then a simulation model is created using the maps (Matloff 2008). It then performs various what-if optimisation scenarios and finally, implements the best and most productive case.

In simulation modelling, a real-life situation can be mapped in three ways;

- **System Dynamics (S.D).** System dynamics modelling was developed by Jay.W.Forrester in the 1950s. It is the examination of information-feedback attributes of business processes to demonstrate how time delays (in actions and decisions), augmentation (in policies) and organisational culture interact to affect the success of an organisation (Forrester, 1958). System Dynamic's implications can be seen in social, urban and ecological sorts of systems.

- **Agent-based Modelling.** Agent-Based Modelling is a method to simulate the interactions and actions of autonomous agents to assess their effects on the system as a whole. These agents can be groups, organisations or even individuals like cars or people, etc. (Grimm and Railsback, 2005).

- **Discrete Event Simulation**. This type of modelling is based on the concept of block charts, resources, and entities that describe resource distribution an identity flow. These entities and objects can be items, boxes, people or cars, etc. This method roots back to 1960s when Geoffrey Gordon comprehended and developed the idea from GPSS and implemented in IBM.

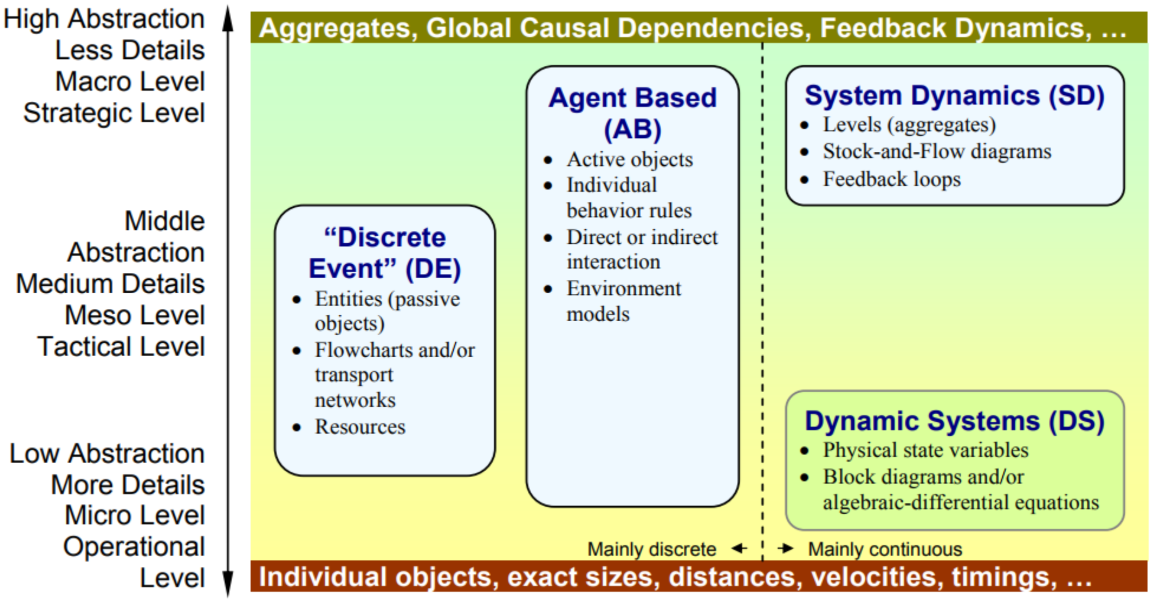


Figure 2.3 Relationship between Discrete Event, Agent Based and System Dynamics Modelling, Borshchev, (2004)

There are so many criterions to differentiate the types of simulation modelling. However, these are the three dominant paradigms in simulation modelling. They differ from another on the basis of their functionality and the kind of input data they require. From the Figure 2.3, it can be seen that System Dynamics is macro level modelling used in strategic levels, has a high degree of abstraction and fewer details. Agent-based is the middle abstraction method utilized in the tactical levels and has a medium amount of details as compared to other methods. Lastly, Discrete Event is the lowest abstraction and most specific type of modelling that used in operation levels and involved micro-level information.

This research has utilised discrete event simulation in the case studies as this method is most suitable in the process optimisation scenarios (Brailsford and Hilton, 2001). The input data that it uses is the micro level, detailed and imported from real-life cases, which means the outcomes will be evidence-based and easy to be implemented. These three methods differ with each other on the basis of the amount of available information about the process. There are operations where simulation techniques can prove highly beneficial and then there are places where it can just be a waste of time and resources. It is essential to determine the requirement of any tool before using it and ensure that it will deliver maximum benefits. Banks (2004) and Banks et al. (2010) have described some purposes where simulation can and cannot be used as an appropriate tool.

Table 2-1 When Simulation Can and cannot be used

When Simulation can be used	When Simulation cannot be used
Studying internal intercommunication of complex systems or subsystems within a complicated arrangement. (Law and Kelton, 2000)	Simulation is not really useful if the problem is relatively simple and be answered with other simplistic tools (Banks *et al.*, 2010).
Simulating any as-is system and study its effects in a computer-based environment without disturbing the actual system. (Borshchev, 2014)	When the cost to conduct direct experiments is lower than simulating it and then performing what-if scenarios
Suggested improvement based on the alterations raised in the computer-based model	Simulation models rely on accurate data; if that is not available, it will be a waste of time
Changing various inputs in the system and studying the effects on the outputs, i.e. different what-if scenarios (Pedgen, Shannon and Sadowski, 1995)	If specific resources are not available for simulation modelling, it will not give maximum benefits
Reinforcing different analytical solutions and methodologies and verifying them as well (Banks *et al.*, 2010)	If any issues can be resolved analytically
Experiment with new layouts and designs of facilities before actually creating them in real (Hoover and Perry, 1989)	If the system behaviour is too complicated and there are so many variables that cannot be defined
The conduct of any model can be visualised, and researchers can learn any hazardous situation.	If the model cannot be verified and validated, there is no point in spending efforts in making one.

2.3.1 Information Provided by Simulation

Simulation is usually used as a problem-solving approach. If appropriate layouts and input data are available, a simulation model can be developed to study the behaviour of the system which is yet to be established in real life. After creating a model, different inputs and layouts are modified to investigate the effect of these changes and come up with the most efficient design. After exploring various what-if scenarios, one of them can be chosen as the most efficient solution and then implemented in real life (Hoover and Perry, 1989). Some of the general benefits are described by Pedgen et al. (1995) that are displayed in the picture below:

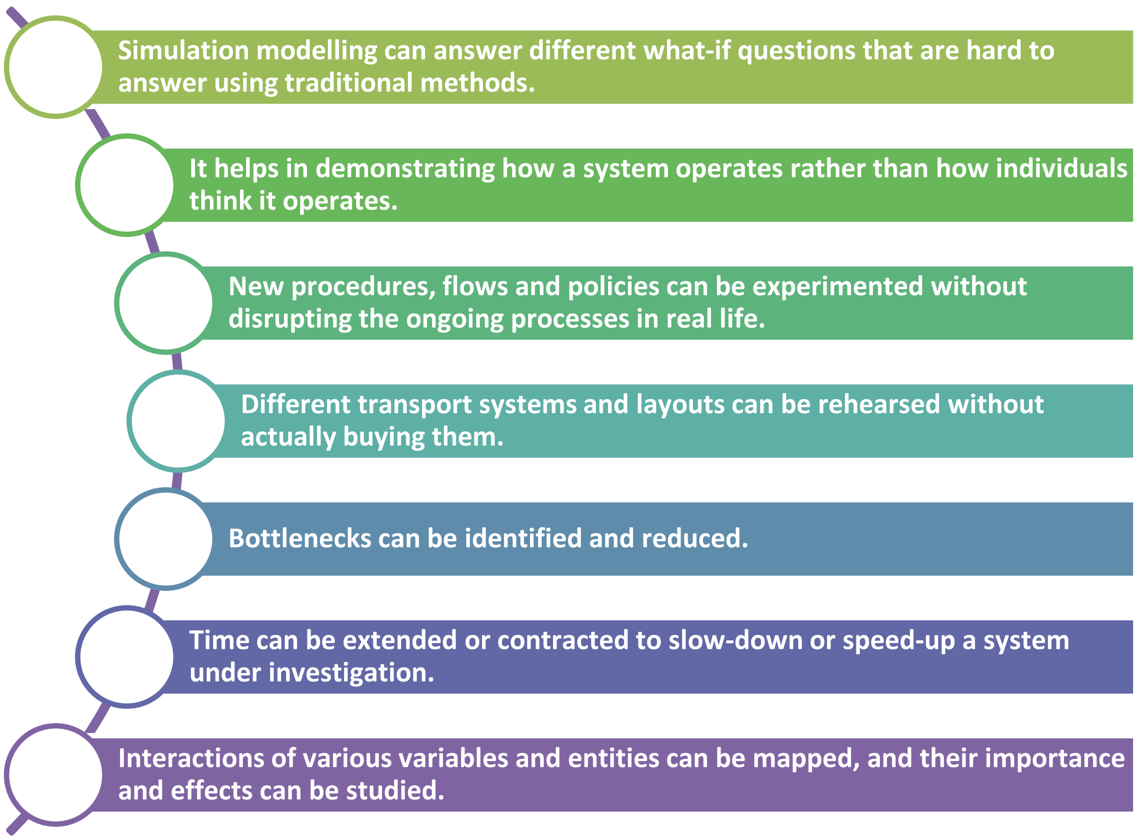


Figure 2.4 Various advantages of Simulation modelling, Pedgen, Shannon and Sadowski, (1995)

This technique is widespread now, and the manufacturing sector has benefitted hugely from its applications. It breaks down complex processes into small events and helps to investigate them its detail. Companies often spend a lot of resources on producing Computer Aided Diagrams (CAD), new layouts and different process maps. Even these activities cannot forecast the actual results precisely, whereas simulation modelling can help in investigating the capability of new design or changes and can help decision-makers by providing critical implementation support (Bhasin, 2015).

Mathematical modelling including Simulation is the second most used methods as a research technique that is mentioned in various journals of Supply Chain and Logistic Management (Sachan and Datta, 2005). Computer-based DES has been used for analysis of supply chains and logistics systems for a long time (Manuj et al., 2005). There are major variations and uncertainties to consider in these systems, and the ability of simulation to take account of stochastic conditions make it strong decision-making and research tool (Lee et al., 2002; Longo and Mirabelli, 2008).

These advantages can be seen as possible opportunities; however, it should be noted that they come at some cost and a company or business cannot benefit from it in many circumstances mentioned in Table 2-1. One should carefully assess other options before jumping to simulation as it can be costly. Appropriate skills and knowledge are required to build a simulation model, and different software is needed which can cost significant amounts of money. Another issue with simulation is that if two people develop a model of the same environment, both these models will be different from each other. The results will not vary too much. However, it can be confusing and becomes hard to extract the results (Flores, 2015). Many assumptions are made while making simulation models which can sometimes lead to random outputs. Hence, it can be challenging to separate results by randomness and interrelationships (Banks *et al.*, 2010).

Creating simulation models and analysing its results can be expensive and time-consuming. Simulation modelling is cheaper and faster today than it was in the past and will continue in future. However, it is not the most economical available solution to many problems (Pedgen, Shannon and Sadowski, 1995). Simulation modelling can facilitate the validation of future state. According to Law and Kelton (2000), validation is a method which assures that the developed model imitates the actual system. It makes the model more credible and strengthens it (Grimard, Marvel and Standridge, 2005). Simulation models can provide enough information to expedite and verify the decisions of executing lean manufacturing techniques. It has also assisted organisations during the implementation stage to achieve the aspired results (Abdulmalek and Rajgopal, 2007).

As described in chapter 1 that no optimisation theory or tool is comprehensive and can solve a problem altogether. Lean and simulation are often used as they complement each other in most cases. Marvel & Standridge (2009) explain the style in which simulation is recommended as a fundamental validation method in lean transformation. Simulation helps by iterating the series of experiments until the satisfactory results are archived. Simulation modelling along with lean methodology can assist in reducing waste and maximising productivity. Lean also aims to minimise the activities that do not add any value by mapping the processes and simulation can further enhance it by experimenting with various scenarios that are not possible otherwise in real life due to cost and time factors.

2.3.2 Process of Simulation Modelling

This chapter describes seven main steps in developing a DES model and then utilising its output after verification and validations procedure. This process to form a fully working DES model was proposed by Banks (1998) that explains various steps involved in this journey. Similar measures are and will be used in this research to achieve the desired solution.

2.3.2.1 Define problem

The aim of this step is to outline the objectives of the whole process and precise queries that a simulation model should answer. It is a critical step, and lack of attention here may lead to inaccuracies and even failures in work (Keebler, 2006). If the purpose of the research is vague and ambiguous, it will result in irrelevant analysis, bad decisions, loss of time and inappropriate inferences (Dhebar, 1993). It is not easy to state a problem precisely, and in quantitative terms, however, it is a good practice to have an iterative procedure to simplify problem formation. Engage all stakeholders at this stage can be useful to ensure that relevant and correct problem is addressed. An apparent problem means that the scope of the simulation model, required resources, performance measures of interest and time frames are quantified correctly and more proficiently.

2.3.2.2 Establish dependent and independent variables

Self-reliant variables reflect system parameters whereas dependent variables consist of performance standards. In the Simulation model, system parameters, i.e. independent variables are worked with, and the resulting reaction on depending variables are logged to investigate. The analysis of these variables yields solutions to the issues described above. The accuracy of the results of a simulation model relies on what is included in it. (Towill and Disney, 2008). Therefore, independent and dependent variables are directed by the purpose of the study and the specified problems which have to be solved with simulation. All the factors, depending on an issue, that can influence the responses should be taken into account like legal, technical, monetary, historical, organisational and economic and psychological factors (Potter and Disney, 2006).

2.3.2.3 Create and validate an abstract model

It is good practice to develop a theoretical or conceptual model before creating the actual model, which mimics the real system in practical life. A conceptual model is set up with the help of logical and mathematical relationships related to the structure and components of the system (Banks, 1998). This step clarifies the objectives, model components, their inter-relationships, algorithms assumptions, concepts, data summaries and other model aspects to understand and describe the problem thoroughly (Sargent, 2007). It increases the credibility of the model that will be developed in later stages and will help researchers in fixing errors and omissions that will cost more after development (Law, 2009).

2.3.2.4 Collect data

Collecting data is usually a challenging part as there can be various unforeseen encounters in acquiring appropriate data. Sometimes, it is not available in the desired formats or level of detail which makes it hard as discrete event simulation requires the maximum amount of features with lowest abstraction possible (Borshchev, 2014). The first step is to establish the necessary model parameters, operating procedures, system layouts and probability distributions of chosen variables. After acquiring the data, it is important to scan and verify the data to minimise any discrepancies.

2.3.2.5 Create and validate the computer-based model

A model is built by using simple steps in the beginning, and it automatically starts to become complicated at the end of the project when all the details are incorporated (Banks, 1998). There are various packages to develop simulation models, and all of them have unique abilities that are further refining with time. Once a model is generated, and it starts producing results, it is essential to verify the results at early stages by comparing the results with the ones obtained from the conceptual model. According to (Sargent, 2007), most accurate results can be achieved if the verification is repeatedly done while developing the computer-based model.

2.3.2.6 Perform simulations

After developing and verifying a simulation mode, different replications are run by changing warm-up periods and run lengths to achieve more accurate results. Different what-if scenarios are experimented at this stage to improve the process, or to make future modifications safely. Computer-based simulation programs have to be run several times to reduce the standard deviation of the sampling distribution (Law, 2007). Different experiments are performed from the micro level (machinery) to process scale level to gain maximum benefits.

2.3.2.7 Analyse and Validate Results

Once the simulations are performed, the results have to be examined and approved. If the results of the computer-based model are aligning with those of the conceptual model, it means computer model has been made accurately, and the results are reliable. Various what-if scenarios are practised in a computer-based environment, and they have to be validated by people from industry or other relevant experts. After validation of results and financial assessment has been done, these experimented scenarios can then be trialled in real life.

Simulation process follows a particular method to achieve its objectives. Figure 2.5 below shows a standard simulation journey mapped by Banks, (2004) and Flores, (2015).

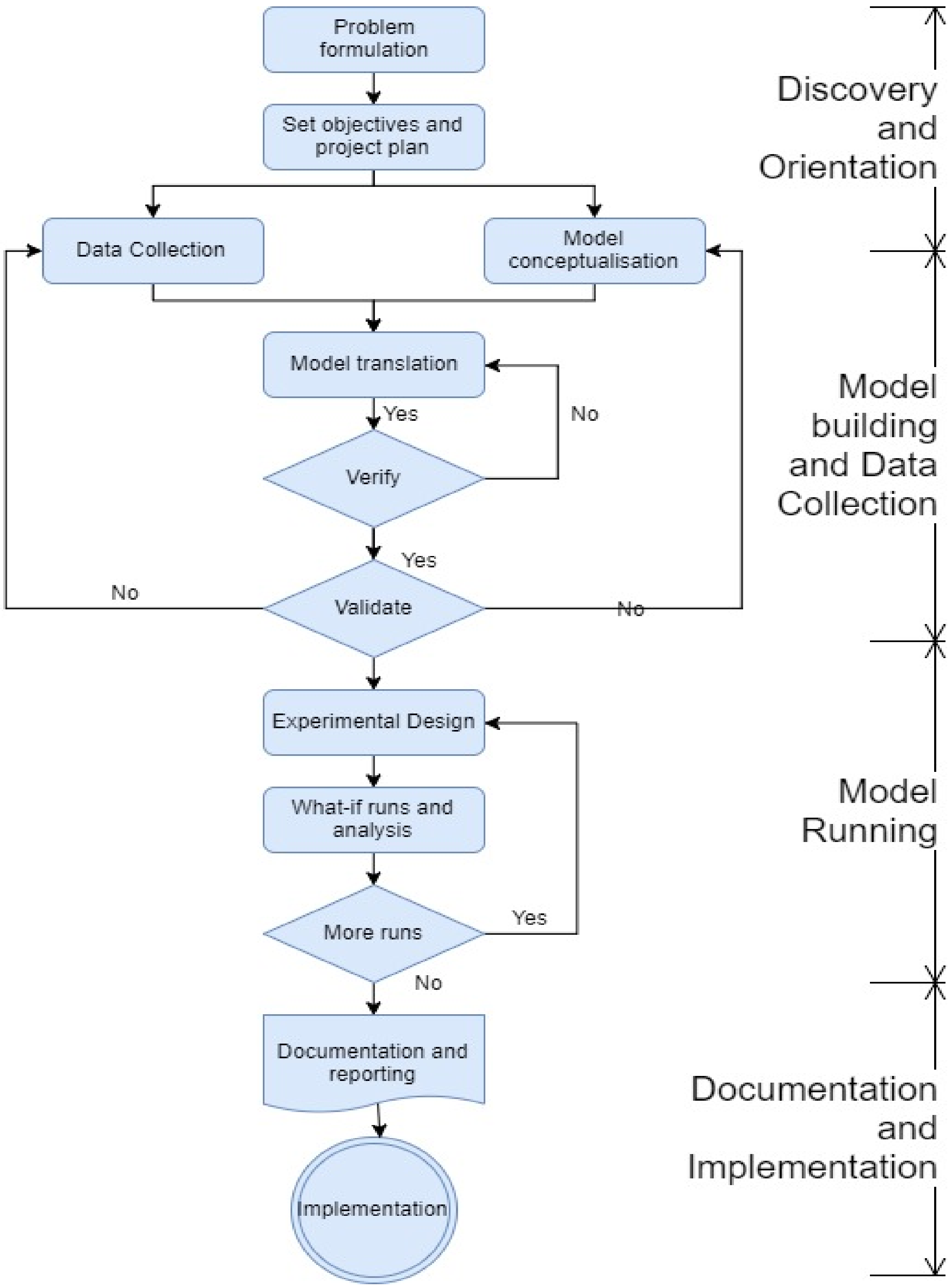


Figure 2.5 Different phases of simulation modelling according to Banks, Flores 2015

It starts with problem formulation and setting aims and objectives to achieve it. Once an issue has been chosen through literature review, interviews or personal experience, then data is collected around it to create a conceptual model. This conceptual model paves the way for future steps and outlines the activities that will be followed after it. A simulation model is then created in a computer-based environment, and it is then verified and validated by interacting with experts and seniors in that particular field and simulation modelling.

If the feedback or suggestions during the validation process are dominant, it goes back to the conceptualisation stage which is then revised. After validation, different tests are run, and various what-f scenarios are experimented to reach the most efficient situation which can then be executed. The whole process is documented at this stage, and the best scenes are then implemented in the desired operation.

2.3.3 Simulation Packages Used for Modelling.

The simulation software used for this research work will be Simio. More than 90% of the work is performed in Simio due to its strong analytical power, high scale 3D graphics and ability to adapt. Some of the work was completed in Flexsim to avoid bias in results. Simio is fully object-oriented with process and objects being defined graphically with no programming. Another great feature is the addition of Risk factor in the scheduling which many other packages lack.

Another huge reason is the pricing. Simio's free version covers many functions without the need to buy the actual software. Its academic licences are quite affordable, and the academic license was purchased for this research work for two years consecutively. Another option to choose was that Simio could be installed on more than one computer using the same license which the author required. Lastly, its ability to import 3D objects and its visualisation was far better than any other software on the market. Due to these reasons, it was chosen as the primary software to be used for the modelling of two case studies.

Simio has a modern Microsoft ribbon style interface that assists with efficient navigation. Tooltips found throughout the products make learning and discovery easier with less reliance on external documentation. It uses the latest Dot Net technology which means advanced industry users can extend the Simio model by creating custom objects, rules or interfaces etc. In Simio a model can be produced in 2D and 3D at the same time. By default, a user is looking in the window in 2D, but it can be switched to 3D by merely pressing the three button the keyboard which is an excellent feature of Simio. The grid is an excellent assist in importing the foreign objects to the Simio on the scale, e.g. the resurfacing vehicles, dump trucks and excavator were al imported using Google Trimble 3D warehouse into Simio and were adjusted using the scale.

Simio can place the images as backgrounds of a simulation model which can be used for designing a factory layout or airports or classrooms, however, in this research work, it was used to import the real map into the system. Once the interactive map was used as background, all the model was developed on top of it using vehicles and other resources. The auto-rotate feature can rotate around the process to view from different angles; however, the camera feature allows a user to view the environment from the eye of an object or resource present in the simulation model. This way a user can see a bird's eye view of how any entity travels through the system. Some of the objects can also interact with other and easily make smart decisions.

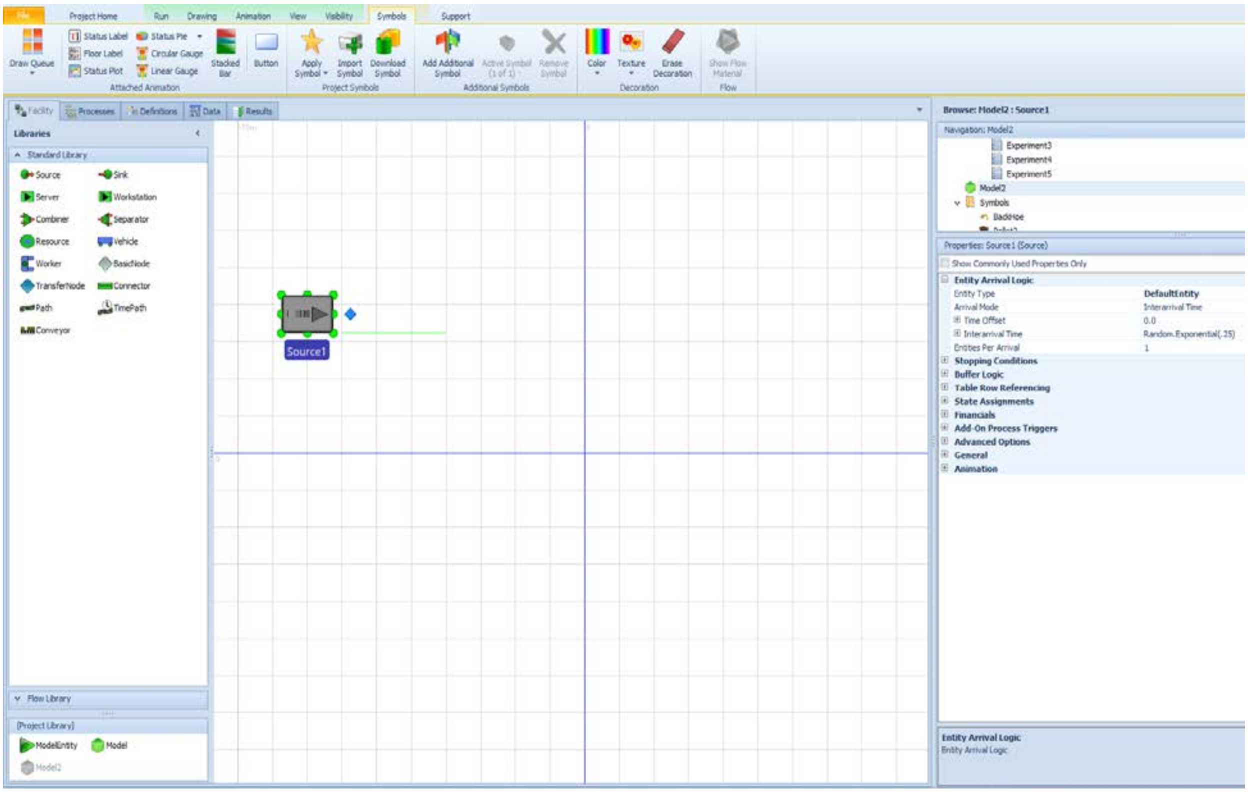


Figure 2.6 Primary interface of Simio software.

Figure 2.6 above shows the primary interface of Simio software when it is opened fresh. Simio has a ribbon-based interface. On the top, it shows project home, new experimentation menu, running times, visibility tools, grid and the support ribbon. It also has Simbits on the top right side. Simbits are small simulation models which are designed to guide user about the functionality of various features in Simio. In the top ribbon, it also shows a symbol and import symbol sign, which means either a user can have these standard symbols or can import a design he created himself or import from Google Trimble library that has millions of object files available for free. One the left side, it has objects library with objects like vehicles, operators, machines, servers, paths and nodes etc. These are only the standard objects, and more objects are available in the advanced options. All these options can be dragged from the left side and dropped on the centre of the white screen to have them in the model.

On the right side, it displays different models that are in a system. Below that, it has properties tab, which is the most important and most used tab of the software. All the objects have some fundamental properties like speed, position, size, schedule, idle time, location and other characteristics. To obtain a fully functional and accurate model, all these properties for each object have to be defined precisely. For instance, when a server is placed and selected in Figure 2.6 above, it is showing various features of Server object like entity type, arrival mode, interval time, stopping condition and add-on process triggers etc.

Entity type means what kind of entities the model will be using; either it is people, cars, bottles or boxes. Arrival mode can be selected using inter-arrival time, fixed time or using a custom-designed schedule in excel. Stopping condition means certain conditions when the source will stop producing entities; it can be the shift-end time or a breakdown of any machine in the system etc.

More details about the interface and running of the software are provided in section 4.5 and 5.5.

2.4 Six Sigma and current improvement techniques

There are many manual-based process improvement methodologies that have evolved over time (Events, 2005). Most of them originated from the Toyota production and all of them aim to improve the production of the effectiveness of an overall system, an operation or a specific process. Some of these methods gained a lot of attention during the last few decades, and Six Sigma is one of them.

Six Sigma started at Motorola and then evolved as the core of the policy at General Electric. Since then, it has been applied in various business processes for improvement purposes. It helps the companies to identify and quantify inconsistencies and defects in any process to deliver impeccable services and outputs (Evans and Lindsay, no date). It is a project driven management strategy used to improve the company's services, processes, and products by continuously decreasing the deficiencies and weaknesses in an organisation (Kwak and Anbari, 2006).

The implications of Six Sigma in various industries are remarkable. During 1999, General Electric utilised this method and spent about $500 million on its implementation and then saved over $2 billion as profit for that year. (Pande, Neuman and Cavanagh, 2000). The principal purpose of this method is to remove the defects from the processes and look at the overall process from end-customer's perspective.

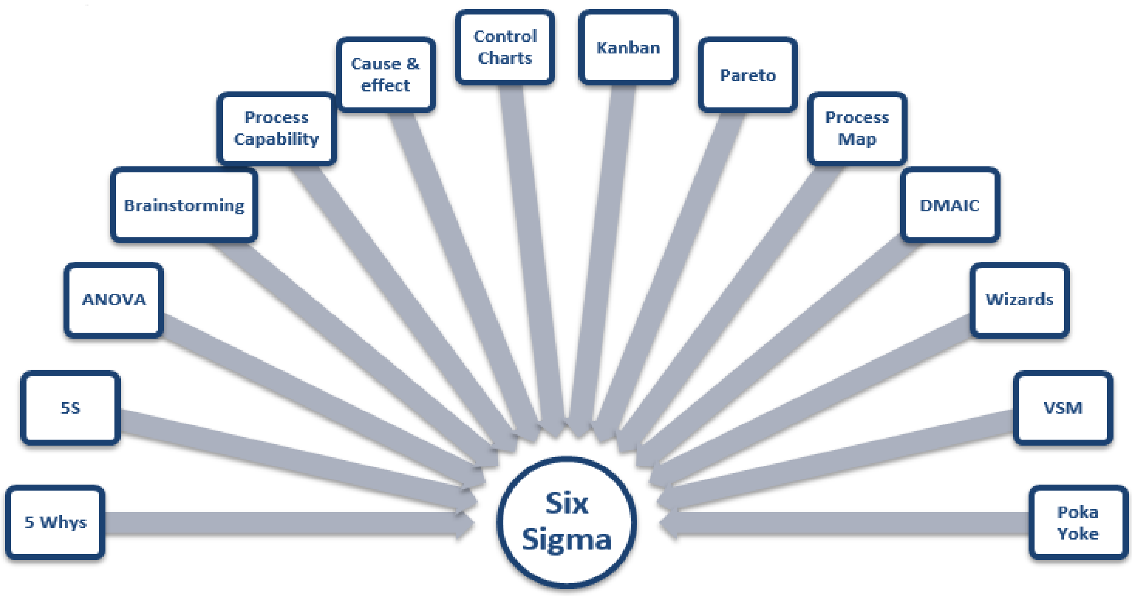


Figure 2.7 Different tools of Six Sigma.

This gives it an ability to lessen the unwanted activities which individuals in the business do not realise as waste. Six Sigma is a developed methodology now, and there are more than 37 tools within the Six Sigma approach. Some of them are shown in Figure 2.7 above.

2.4.1 DMAIC

DMAIC (Define, Measure, Analyse, Improve, Control) is a function used for problem-solving and is similar to its predecessors like Seven-Step Method and Plan-Do-Check-Act (Balakrishnan *et al.*, 1995). It is used as a method to design new organisational routines by understanding the current procedures and mapping those (Schroeder *et al.*, 2008). DMAIC is a process improvement and problem-solving technique and is an instrumental part of Six Sigma methodology (Chakravorty, 2009).

In Six Sigma, two sub-methods are used by engineers, 1) DMAIC to improve an existing process and 2) DMADV to develop new activities. DMAIC is more popular as it is utilised for process optimisation and waste reduction in almost every industry from health care to nuclear power generation. Figure 2.8 below shows the 5 stages of this method that are defined (identification stage), measure (evaluation of the as-is process), analyse (assess the causes of waste and how to reduce them), improve (creating a solution and implementing it) and control (disseminate the lessons learnt) (De Mast and Lokkerbol, 2012).

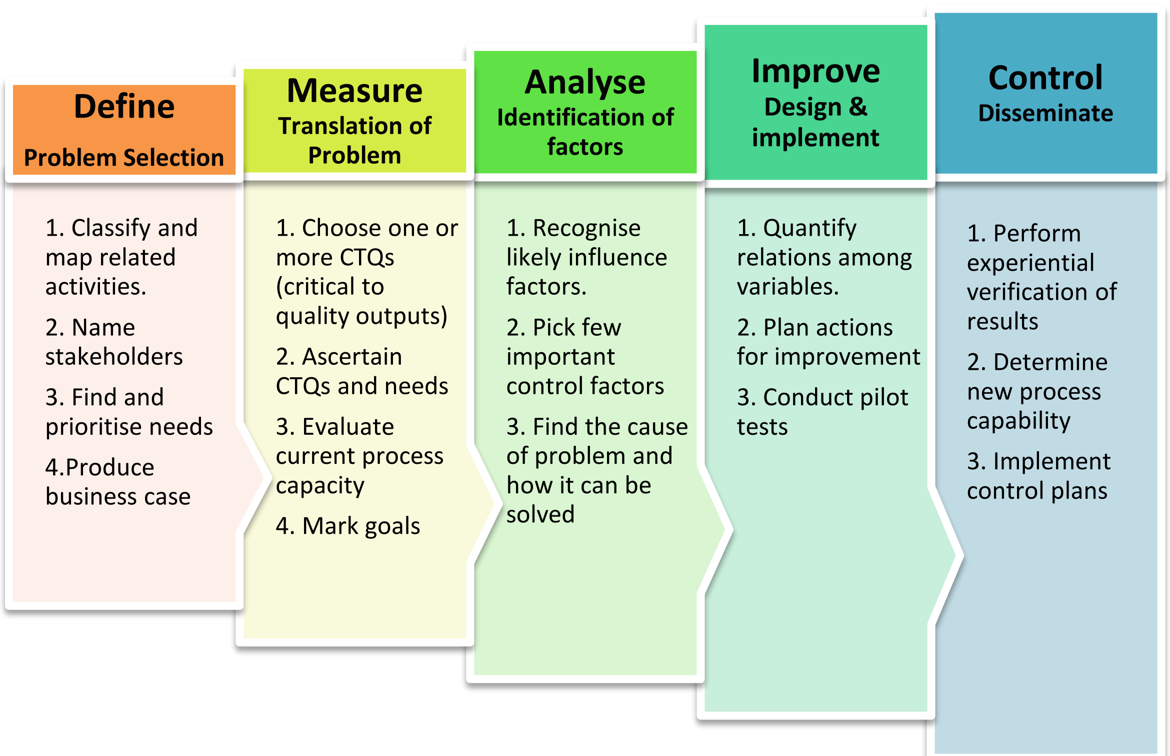


Figure 2.8 showing 5 steps of DMAIC methodology and their brief description

2.4.2 Fishbone Diagram

No tool or methodology in the literature is sufficiently comprehensive and complete, so they often use other methods or their tools to understand the situation entirely (Oakland 2003). Same is the case with DMAIC, where other tools like Fishbone diagram are used to explain the reasons behind non-value adding activities and other wastes. It is called fishbone because it's completed picture looks like a fishbone structure (Vertex42, 2013).

This diagram is also called Cause-and-Effect diagram as it helps in understanding the relationship between them in various processes (Yazdani and Tavakkoli-Moghaddam, 2012). The head of the figure depicts the problem statement, and the bones or lines categorise different causes. In most of the cases, the categories are made up of process, materials, equipment, management, environment and people. They are also called as 6 Ms to easily remember which are manpower, machine, materials, measurement, milieu and methods. Figure 2.9 below shows a sample of Fishbone diagram made for resurfacing operations.

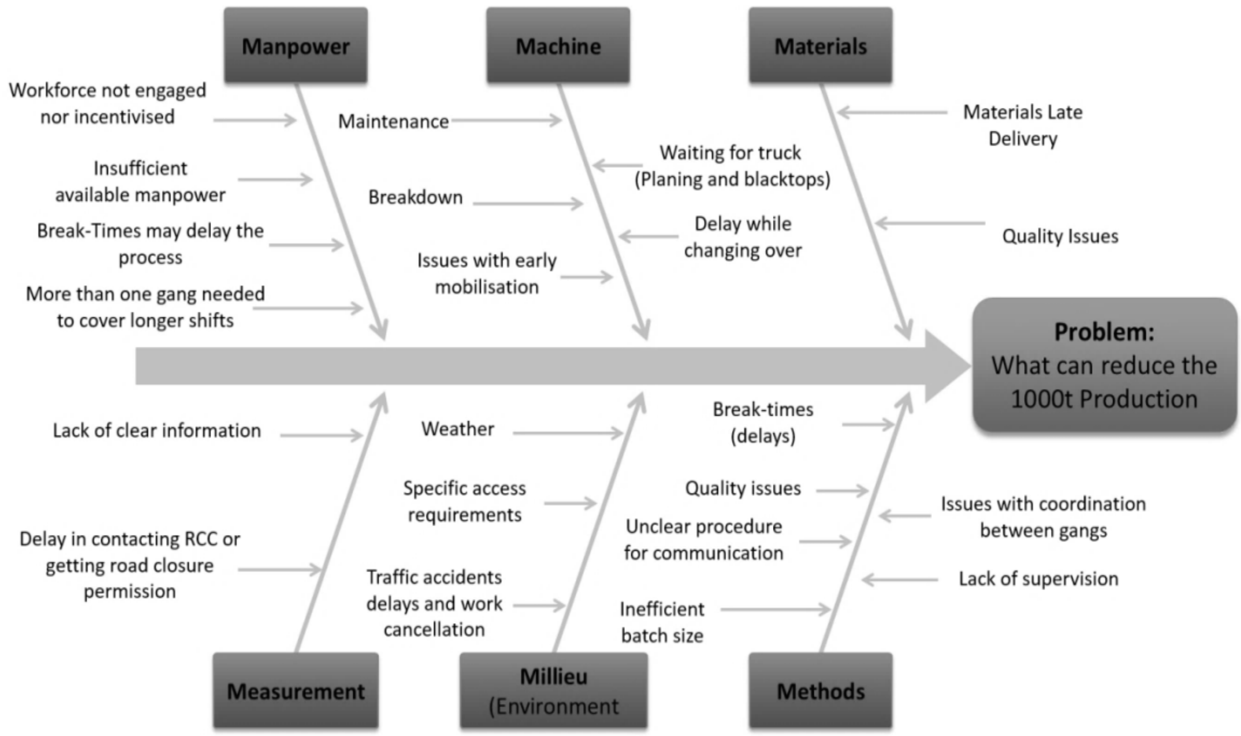


Figure 2.9 Fishbone diagram of 1000 tons case study, Aziz, Qasim and Wajdi, (2017).

2.4.3 Process Mapping

Process mapping is a management tool created and used by General Electric as a strategy to improve their business performance. It uses workflow charts and related texts to represent every vital step in the business process. It has been proven as communication and analytical tool which intends to improve the existing process by altering or creating a new process-driven model (Hunt, 1996).

Process mapping involves creating a model that represents connections between people, objects, data and activities participating in a formulation of a particular output (Biazzo, 2002). This method is prevalent these days due to its ability to offer inexpensive, and useful descriptions that can help in re-designing processes and growing efficiency (Colquhoun, Baines and Crossley, 1996). In process mapping, any particular process is investigated in in-depth detail, and then several activities are categorised and arranged in the order they usually follow. Figure 2.10 below shows an example of a process map that was drawn by the author for resurfacing operations.

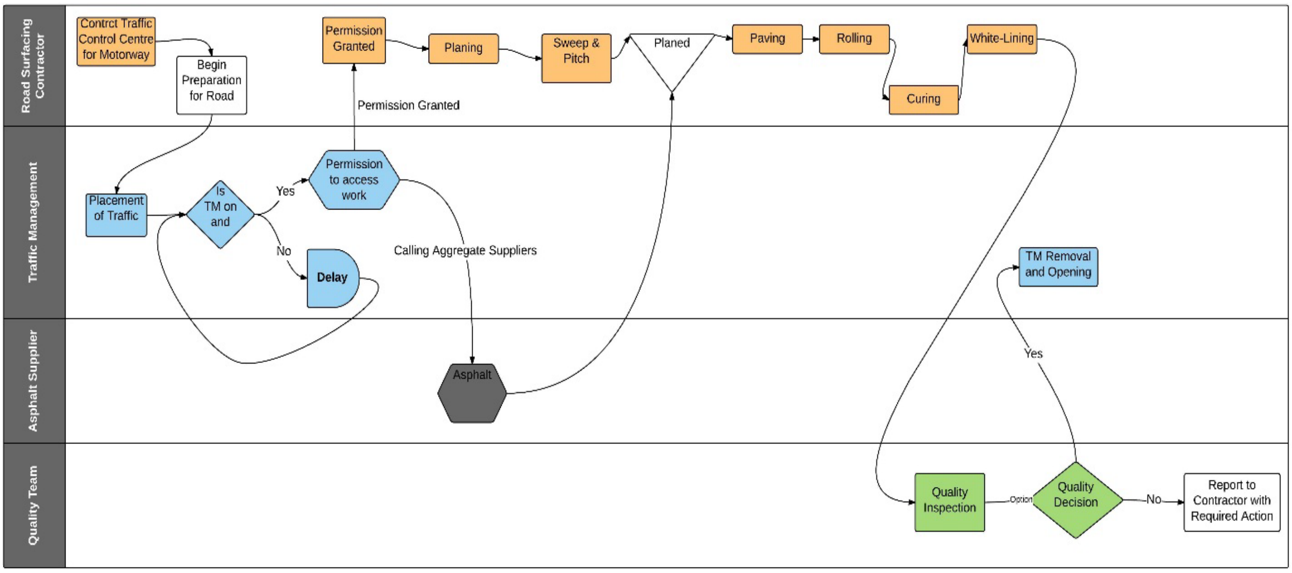


Figure 2.10 Process Map of 1000 tons case study, Aziz et al. (2017).

2.4.4 Analysis of Six Sigma

Six Sigma is a popular tool used in various industries and sectors from defect identifications and removal and for process optimisation purposes (Snee, 2000). Massive savings can be made using this methodology and its tool over the years for any size or type of business. However, it demands extraordinary management capacity, focus on customers, and training in tools, team processes, change in organisational culture and problem-solving approaches (since it has elevated the need of statistical thinking in business development). (Antony, 2004). These factors make it hard for many companies to implement it efficiently. Since there is no tool which is sufficiently comprehensive, Six Sigma also needs to be integrated with other performance perfection strategies to gain maximum results. Hence, it will be wrong to say that it is a magical cure.

Six Sigma has to be applied and repeated for years to gain results. It relies heavily on statistics and accurate data for decision-making more than other competing methodologies (Sherman, 2014). The biggest issue is the change in organisational culture that puts quality into planning. Some businesses that do not understand the limitations of six sigma or without understanding the across-the-board change management plan are most likely to fail. Six Sigma rigorous training of managers and there are different categories (Belts system) that always keep building their capacity which costs the organisations large sums of money (Kwak and Anbari, 2006).

Companies have saved billions of dollars in savings by adopting this method. However, they also spent millions initially to implement it entirely, which is not possible for many businesses (Pande, Neuman and Cavanagh, 2000). Six Sigma can improve a current process using different tools that help in reducing waste, but it cannot overcome the uncertainty which is a critical factor in industries like construction. Usually, there is no clear answer to what-if questions and assumptions are made to fill the ambiguity in models which is not very practical and hinders the maximum achievement.

2.5 Lean Manufacturing

Lean manufacturing aims to reduce costs by reducing unwanted activities. Even though it is called lean manufacturing, its underlying concepts can be implemented in almost every organisation (Williams, 2017). James Womack, called it Lean production to describe the great revolution in manufacturing that was triggered by Toyota production (Womack, Jones and Roos, 1990).

It is a multidimensional method, which incorporates various management exercises like supplier management, just-in-time, work teams, and quality systems within a unified system (Shah and Ward, 2003). Lean can also be combined with Six-Sigma, and many organisations combine these two methods together, and now it's called Lean-Six Sigma. The advantage is that six sigma focuses on quality assurance by removing defects and lean focuses on reducing any waste to gain maximum efficiency. Figure 2.11 below displays various lean tools that are used.

Productivity and competition challenges during the past two decades have forced businesses to adopt new optimisation techniques, and lean is one of them (Shah and Ward, 2003; Womack, Jones and Jones, Daniel; Womack, 2003). Lean is not only a technique but a way of thinking. It aims to develop a culture where everyone is striving to improve the production and process. Like Six Sigma, it is also a customer-focused method that employs customers from inside and outside the organisation, which creates a Pull force from production to delivery (Liker, 1997).

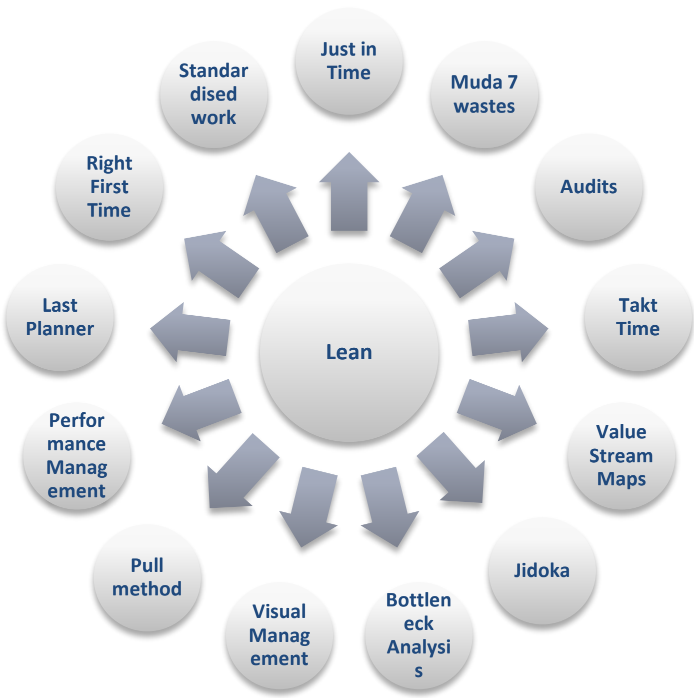


Figure 2.11 Various Lean tools used for process improvement.

2.5.1 Value stream maps.

Value Stream Mapping (VSM) is also called as "Material and Information Flow Mapping" at Toyota. Its fundamental purpose is to map the existing state of a process and reduce waste rather than training people or as a Learn and See method (Rother and Shook, 2003). At Toyota, engineers give plenty of attention to establish flow, reduce waste and to add value which in fact is the methodology of VSM (Singh and Sharma, 2009).

Value Stream Mapping has many advantages like visualising the complete process in everyday language, illustrating relationships between various operations, identifying and eliminating waste and acting as a continuous improvement tool (Seth, Seth and Goel, 2008). The Figure 2.12 below shows a sample process map of a production control system and displays the relation between various components that are hard to visualise otherwise. Value Stream Maps can help in reducing wastes in over processing, defects and skills problems, inventory, waiting times and overproduction issues.

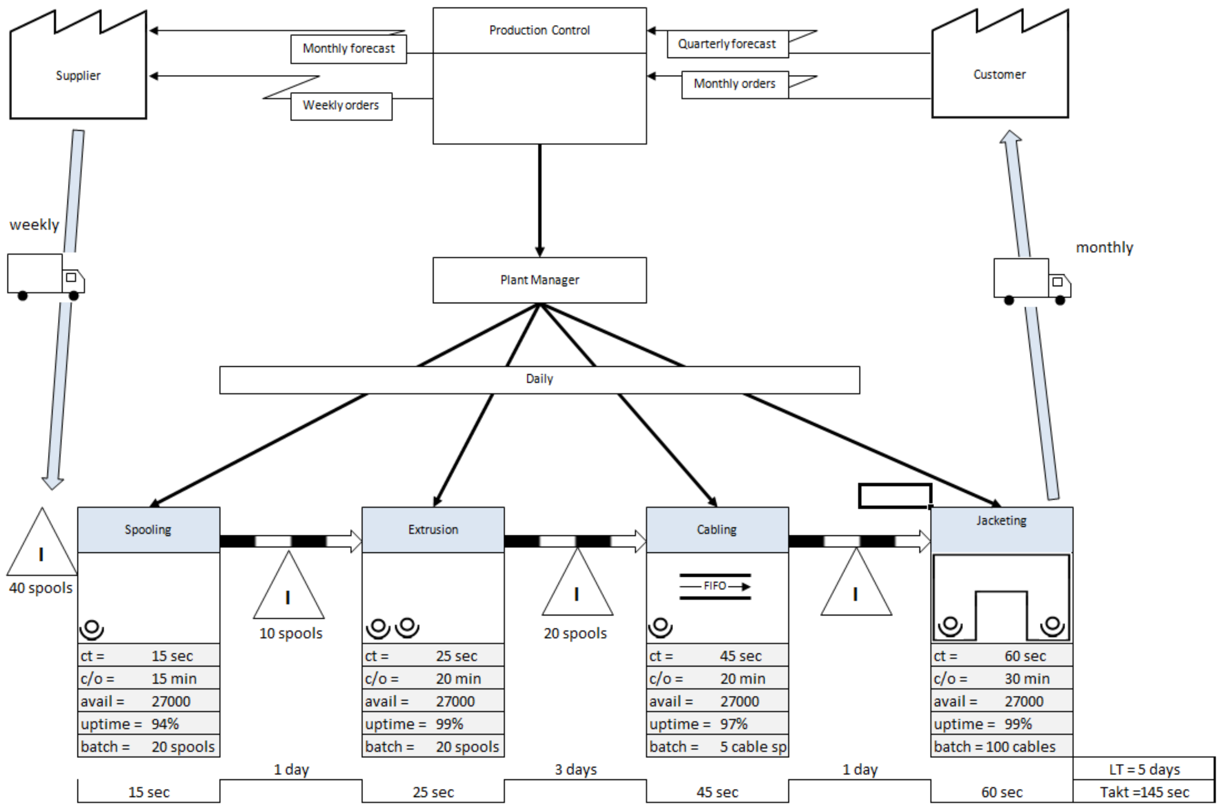


Figure 2.12 Value Stream Map of a production control system, ://www.breezetree.com/value-stream-mapping.htm

2.5.2 5S Approach

5s is a lean system used for process optimisation which works by reducing the waste, improve labour productivity and clean/arrange workplaces (Parrill and Rosinski, 2000). It encourages sustaining an orderly workplace and making use of visual signs to gain consistent and enhanced operational results. 5s is usually the initial lean approach in organisations to expedite the application of other lean methods which improve process parameters and overall structure (Chakravorty, 2009). The 5 S's can be explained as:

1. Sort: Remove items from the working area that haven't being used and save them appropriately.
2. Set the order: Regulate objects that are needed each day so that they can be easily located and immediately stored.
3. Shine: Eliminate any grime and dirt and do it regularly. Make sure all equipment is operating correctly.
4. Standardise: Design a method of procedures and tasks, which will strengthen and support the implementation of these 5 steps every day.
5. Sustain: Develop a culture where people are motivated to follow this culture and then make a record of the efforts.

5s is an organised housekeeping method, which is viewed as the first step towards generating a visual and visible workplace by utilising its visual control methods. (Hodge *et al.*, 2011; Tezel and Aziz, 2016). 5s brings organisation, orderliness, discipline, cleanliness in a workplace followed by several short and long-term benefits. The Figure 2.13 below shows a workshop van before and after the implementation of the 5s method.

Figure 2.13 Before and after implementation of 5s state of a workplace vehicle.

2.5.3 Analysis of Lean Manufacturing

Lean is a traditional practice of process improvement all over the world, and it is used in various forms and shapes. There are some drawbacks as well which have been reported from time to time and have been published. A lot of interest in lean manufacturing methods was based on claims that Japanese manufacturers were twice more efficient than Westerners. However, the criteria to measure the productivity has been criticised heavily after that (Williams, K. Haslam, 1992).

Creating the causal relationships between inputs and outputs is extremely hard in complex systems. Lean can utilise the manufacturing principles in some of the construction and healthcare sectors which possess the same nature most of the time. However, countless projects are unique and traditional approaches cannot help much there (Lewis, 2000). There are various lean methods like 5s and value stream maps which can be utilised in basic operations and small firms. However, many industries do not find them useful due to their different nature. Training the employees is another issue which is usually a hindrance to implementing lean in SMEs.

Regulation of utilisation of labour and speed of work to reduce exhaustion and injuries has been a critical demand of trade unions in Europe, and it goes against the lean principles (Berggren, 1993). Lean production can be used, in most of the cases to improve the as-is process by reducing the waste and non-value adding activities. However, it cannot predict the future events that will affect the operation and its productivity. Like Six Sigma, it cannot answer various what-if scenarios and cannot reduce the ambiguity caused by specific variables. This shows the need to integrate it with other tools and methods which can compensate for its weaknesses in design, maintenance and productivity enhancement in all sorts of projects.

2.6 Total Quality Management (TQM)

Total Quality Management or TQM is the mutual collaboration of all people in an organisation and the related business processes. It aims to generate value for money services and products which satisfy the expectations and demands of customers (Dale, 2015). It predated the Lean and Six Sigma methodologies and gained a lot of attention in the 1980s. It focusses on customer satisfaction. TQM can differ from business to business. However, the companies using TQM usually follow the following principles (Porter and Parker, 1993):

- Companies must follow a systematic and strategic procedure to reach the goals.
- The organisation should identify the main steps of any process and then monitor the performance for maximum productivity.
- All workers work towards same goals.
- Customers decide the standard of quality.
- There must be useful communication skills developed using appropriate pieces of training.
- Companies should continuously find methods to be more competitive and productive.

Figure 2.14 below shows various tools used in Total quality management improvement.

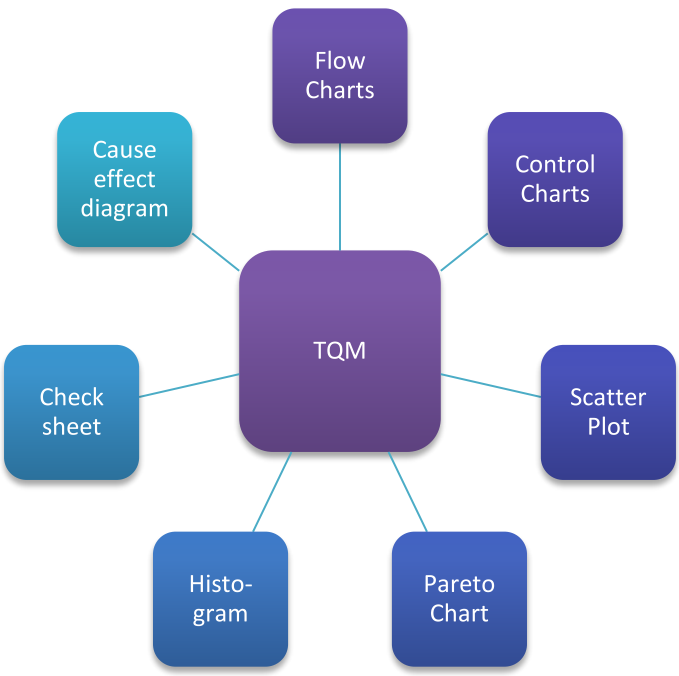


Figure 2.14 Numerous tools of Total Quality Management.

2.7 Combination of DES and Lean

Robinson et al. (2012) explained how simulation could reduce the waste in various operations by integrating with lean approaches, e.g. Muda. Muda or Mudi is a Japanese term which means uselessness and waste, and it is a fundamental concept in Toyota Production System. Taaichi Ohno (1912-1990) who was the Executive of Toyota, identified seven types of wastes that usually affect any manufacturing process (Womack, Jones and Jones, Daniel; Womack, 2003). These constraints exist in construction as well and are responsible for low productivity, reduced utilisation and high waste. Figure 2.15 on the next page shows how these wastes can be identified with the help of the lean tool, MUDA and how discrete event simulation can solve these issues efficiently.

The combination of lean and simulation techniques can lead to an improved corporate image, better process flow, increased compliance with customer's expectations and enhanced employee utilisation, mortality and commitment. It can also reduce the unnecessary material usage, energy consumption, cost and lead time, and water usage etc. The overall results would be enhanced productivity as a whole that will also impact health and safety aspects positively. Different people have been working on the mixture of both optimisation techniques and have termed it as a win-win situation.

The deficiencies in the lean methodology can be overcome by using simulation methods. Future step validation is a critical step in this process which is possible by adopting this hybrid model (Grimard, Marvel and Standridge, 2005). Robinson et al. (2012) explained how lean and |DES are complementary methods from a theoretical and empirical viewpoint. They created a 3 models framework called SimLean in which the simulation was used to facilitate understanding of lean, educate in lean and experiment with various scenarios. Lean concepts can be more readily understood using simulation techniques (B J Schroer, 2004). It helps in the implementation of lean tools and can assist in deciding the application of lean manufacturing floor layouts, which is a significant decision (Detty and Yingling, 2000b).

Many people like El-Haik & Al-Aomar (2006) and Marvel & Standridge (2009) have used the DMAIC approached along with the simulation modelling. The Same combination has been used in this research as well in one of the case studies. It helps in achieving the goals in a stepwise manner while recording all the outputs. They have concluded that simulation makes the lean transformation more accurate and easier (Uriarte *et al.*, 2016).

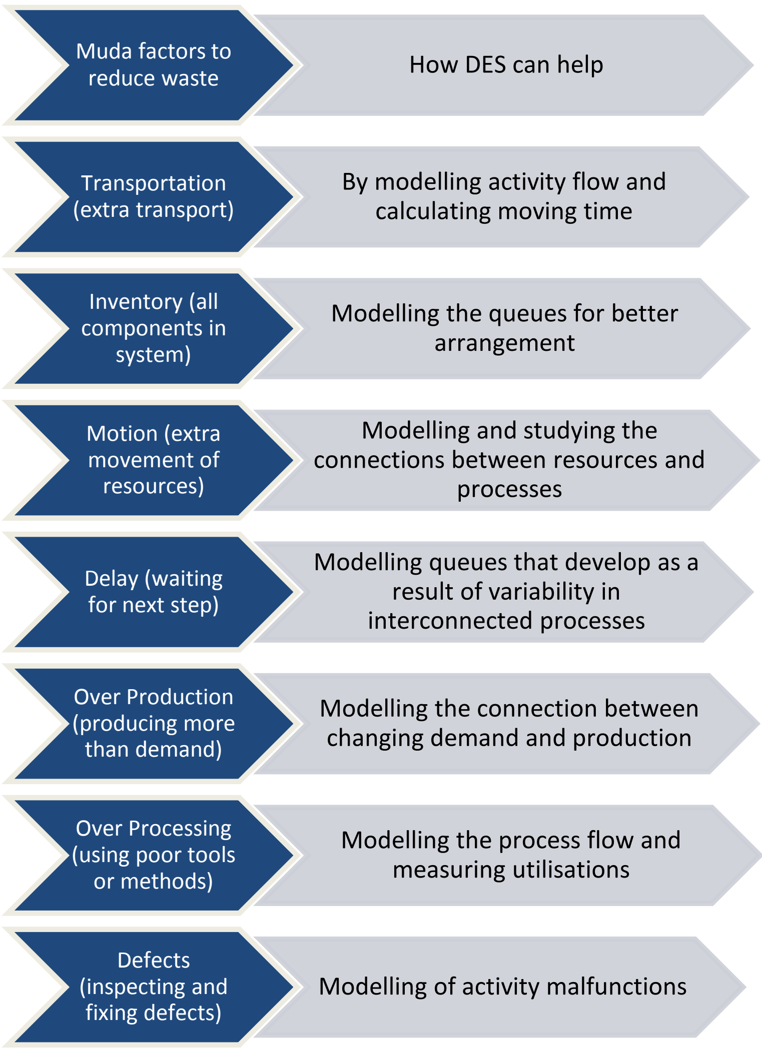


Figure 2.15 How Muda wastes can be reduced with DES.

The literature review demonstrates that Discrete Event Simulation (DES) is one of the most resilient and flexible analytical tools for performing comprehensive system analysis. It can handle almost all issues at nitty-gritty level which lean manufacturing may not be able to zoom into. This is the reason that DES has frequently been used in healthcare, logistics and manufacturing industries all over the world (Abdulmalek and Rajgopal, 2007; Solding and Gullander, 2009).

However, DES is not very famous in the lean community for both academics and industry practitioners. The major impediment lies in the perception that simulation is or can be lengthy, time-consuming, require computing work and specialised training and programming skillsets. This is why majority lean practitioners do not view simulation worth the attempt, particularly during working with a team with a limited background of simulation technologies (Lin, Chan and Kwan, 2017).

Integration of DES and lean appears to be a capable strategy to moderate the perception gaps amid simulation specialists and lean experts (Gurumurthy and Kodali, 2011). Lean can provide an overview structure of a complete process making it easier to identify bottlenecks, waste and overlapping etc. Simulation modelling can zoom into details and perform different scenarios in a computer-based environment to mitigate these issues safely and evaluate or redesign the redesign options.

2.8 Comparing Lean, Six Sigma and Total Quality Management

Lean and Six sigma, both have similar goals. The both aim to reduce waste and develop the most efficient system possible. However, they adapt different methodologies to achieve the same goal. To make it even simpler, the major difference between these two is the dissimilar method of identifying root cause of waste. Six sigma supporters advocate that waste results from the variation within the activities. On the other side, Lean practitioners assert that waste comes from avoidable and non-value adding steps in the construction process (Näslund, 2008). Six sigma aims for near perfect results which will minimize costs and obtain enhanced customer satisfaction. Whereas, lean concentrates on investigating workflow to diminish cycle time and reduce waste. To conclude, the main difference between them is that lean look at methods to maximize workflow and six sigma focuses on realizing consistent outcomes (GreyCampus, 2017).

Both these methods are true in their assessments and this is why they have been successful in improving business processes in several fields over the years. Since there are more similarities between them, they have been proven more useful when mixed together i.e. Lean Six Sigma. The ultimate issue is not to choose either of them, but to implement them efficiently to solve the problems in the business environment.

Six Sigma and TQM and very similar to an extent that some people claim they are same. However it differs in a wat that it was used by people other than just volunteer production staff (). TQM is aimed at overhauling the way that companies do things. Lean Six Sigma is aimed toward obtaining the fastest change possible in a company. While both methods aim at improving quality, there are important differences between them. TQM is aimed at overhauling the way that companies do things. Lean Six Sigma is aimed toward obtaining the fastest change possible in a company. While both methods aim at improving quality, there are important differences between them (Bowen, 2018). Table 2-2 below shows brief but basic difference between the philosophy of Lean, TQM and Six Sigma.

Table 2-2 showing difference between Lean, TQM and Six Sigma

Lean	If organizations want to reduce costs, reduce waste and operate quicker, this is the right method for them. It is great for identifying what means value for the end customer.
TQM	Relatively simple and easy to understand, TQM is well suited for individual projects. It is a very good group of tools for problem-solving after things have gone wrong.
Six Sigma	This is best for high volume activities where stability is required. The tools are similar to TQM but more structured.

Table 2-3 below shows basic differences between Lean/Six Sigma and Total Quality Management. TQM is the oldest methodology amongst them which originated from Toyota production and other two are the latest shapes of this same method. Lean and Six Sigma are very similar to each other compared to TQM that has almost become obsolete now over the years.

Table 2-3 comparing Lean/Six Sigma with Total Quality Management. Adapted from (Bowen 2018)

Lean / Sigma	**Total Quality Management**
Customer-satisfaction-based initiatives for quality improvement	Having a consistent, constant, and stated purpose behind improving quality
Specific metrics that drive decision making	Reducing dependence upon inspections (Lean Six Sigma is very data-intensive)
Seeks to reduce variation that affects quality	Getting rid of fear and hierarchy in the company
Separates non-value work from value work – considering non-value work to be waste	Ensuring everyone in the company has undergone training and that they are working toward quality improvement
Focuses upon speed	Ensuring that education is an on-going process

2.9 Summary of Chapter 2

This detailed chapter started with looking at the research problem, the challenges that are faced by the highways sector in the UK, the construction industry issues are that global and how they can be solved or how an optimisation attempt can be made to reduce the impacts. It then continues to talk about different types of optimisation methods including manual and computer-based approaches. Both of these sorts have been in use for a long time and have proved their efficiency. This chapter then concludes that the combination of manual and computer-based methods (Lean and Discrete Event Simulation) can result in reducing waste from some construction operations.

Chapter 3 : **Research Design / Methodology**

Sections

3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
Research Philosophy and Strategy	Methodological considerations	Constructive Research Approach and Design Science	Constructive Research vs other research approach	Need for Constructive Research Approach	Process of Constructive Research	Validation of solution	Summary of chapters	Case Studies

The foundations of active research rely on the choice of an appropriate methodology to structure the research, collect relevant and reliable data and achieve critical objectives of research (Dave, 2013). There are various research approaches used to solve practical problems, and they all have different strengths and weaknesses under different circumstances. The choice of research methods used in research is subject to the nature and sort of study being conducted.

3.1 Research Philosophy and Strategy

Research philosophy correlates with the creation of knowledge and its nature (Saunders, Lewis and Thornhill, 2007). It involves some significant assumptions about how a researcher views the knowledge and how it is developed. This investigation intends to create a simulation-based solution for various construction operations to boost their productivity. Therefore, it requires an accurate set of activists to achieve the defined aim and objectives. However, at this stage, it is critical to know the philosophical positions that are ontology, epistemology and axiology (Miles, Huberman and Saldaña, 2014). They have been briefly described as:

- Ontology explains the researcher's view of the nature of reality. It tells about what assumptions do we make about the way in which the world works (Saunders, Lewis and Thornhill, 2008). It ranges from anywhere between idealism and realism. Sexton (2003) has described realism as the usually encountered external reality with planned nature and structure, and the idealism as the esoteric reality understood in different ways by people.

- Epistemology explains the nature of knowledge. It presents the researcher's view on what constitutes acceptable knowledge and what is the relation between the knower and the knowable. Positivism and Interpretivism are its two extremes. The positivism idea is the search for general laws and cause-effect relationships by rational means. While interpretivism is the pursuit of an explanation of human action to understand the way in which world is perceived by individuals.

- Axiology describes what values go into the research (Sexton, 2003b). Its two climaxes are value-free and value-based. Value-based research is value-laden and subjective, while, value-free research is value-free and objective.

Ontologically, this research brings ideas into reality, and it has an objective and realist's view. Epistemologically, the design researcher knows that the information is based on facts rather than imaginations and individual opinions. Axiologically, the research is creating values, it will depend on the values that are put as input variables, and it will be fluctuating between two extremes. After defining the philosophy of research, a suitable approach is also needed to adapt. Therefore, the development of a simulation model is a positivist and realistic approach.

3.2 Methodological Considerations

Research methodology introduces the procedures and principles of rational thought processes that are implemented in scientific research (Fellows & Liu, 1999). The belief which instigated this study was that construction productivity in general, and highways sector, in particular, could be improved using the latest simulation tools and techniques. The author is more concerned about the process improvements that can be achieved rather than the intricacies of the technologies (even though they have been mentioned in detail). The methodological approaches utilised by doctoral students are frequently controlled by a tight array of social science methods. Costley & Armsby (2007) suggested that some alternative techniques may also be developed that can mainly be applied in practitioner research context.

Chynoweth (2014) analysed the previously expressed methods of practical research utilised in art and design and distinguished between two substitute procedures, i.e. research through practice and research for practice. Research for practice may be described as the study performed separately from the area of practice, but the intention is to develop a new solution or knowledge that can eventually be applied back into a practice setting. Aken (2004) termed it as "Design Science" research as it differs from traditional explanatory research methods.

Research through practice also intends to develop a solution for the industry-related problem. However, it involves a practitioner itself rather than a researcher making it more like Action Research. This industry-related research question, which is discussed in section 1.2 falls within the realm of construction management and information science. This research utilises the “Research for practice” method.

This study adopts “Design Science (DS)” or “Constructive Research Approach (CRA)” as key methodologies. It is a problem-solving model, a vibrant and motivating choice for many researchers who aim to solve real-world problems while producing an academically valued theoretical contribution (Hevner et al., 2004; Pasian, 2015). The word “construct” in constructive research approach is used in this perspective to indicate the new contribution to be established in due course. Similarly, in the design science approach, this construct is called “artefact”. This “construct” or “artefact” can be a new model, process, organisation chart, theory, framework, software or an algorithm. According to Lukka (2003), all such human artefacts are constructions.

CRA relies on various research tools and is associated with positivist epistemology, interpretive epistemology and empiricism. This question-driven research strategy is a logical arrangement which connects empirical data with initial research questions and eventually to its conclusions (Oyegoke, 2008). This approach is applied more frequently in computer science methods as it requires a way to validate, which does not have to be as empirically based like other sorts of the investigation, e.g. exploratory studies.

Figure 3.1 below presents the factors (left) that contribute towards the formation of the construct and also display its implications in practice and theory (right side). The constructive research question can be driven by a phenomenon, theory or combination of both. The purpose is to recognise and resolve real practical problems. It begins with the identification of a practical problem which is also complemented by relevant literature. A research question is then created to solve the identified issue, and issues are solved by constructing a solution that is practicable and appropriate. It can be said that the constructive research approach is linked to quantitative and realistic paradigm (Pasian, 2015).

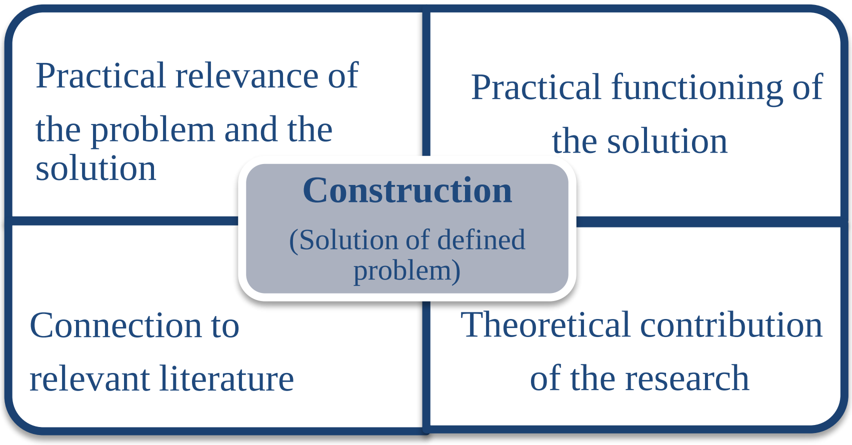


Figure 3.1: Elements of constructive research, Lukka, (2003).

According to Lukka (2003), there are six main steps involved in constructive research approach:

1. Choosing and defining a practically relevant real-world problem.
2. Gaining an extensive understanding of the area (data collection).
3. Designing an applicable solution to the defined problem.
4. Validating the feasibility of the developed solution.
5. Connecting results back to theory and showing their practical contribution.
6. Investigating the application of results to develop a construction.

3.3 Constructive Research Approach and Design Science Method

Design Science (DS) approach and Constructive Research Approach (CRA) are quite similar in terms of problem identification, methodology and results. DS is a relatively new approach based mostly on CRA, and both of them aims to propose a unique solution to the identified problem. Different critical comparisons have been performed to determine the dissimilarities. However, it is seen that they have more similarities between them than differences.

The basic logic of diagnosis in DS is of a deductive nature, where an investigator applies a kernel theory of DS for resolving a problem that was not solved before (Piirainen and Gonzalez, 2013). This way, various general principles from the theory can be applied to a particular problem that will also contribute to theory by providing solutions grounded in it.

On the other hand, the solutions in CRA are based on the profound understanding of the issue and utilisation of current theory through a heuristic method (Dave, 2013).

Figure 3.2 below shows the methodological steps required to carry out research. All the steps are connected to each other, and one is not possible without the other. This clarifies the scope of work, demonstrates challenges that can be faced and constructs a roadmap in mind that has to be tracked. It has been divided into 5 significant steps that are further divided into sub-steps. It will cover all the significant aspects of the research and then develop a solution or artefact for the described problem in step 1.

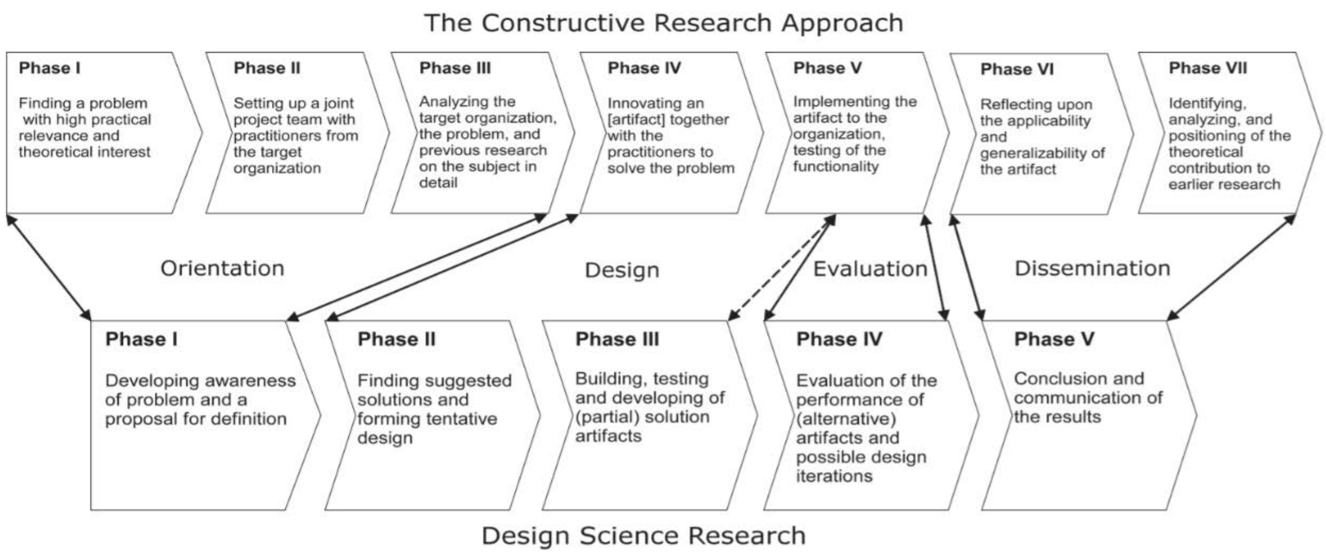


Figure 3.2 Different working style of DS and CRA, (Lukka, 2003; 2006 (CRA); Vaishnavi and Kuechler, 2004 (DS)).

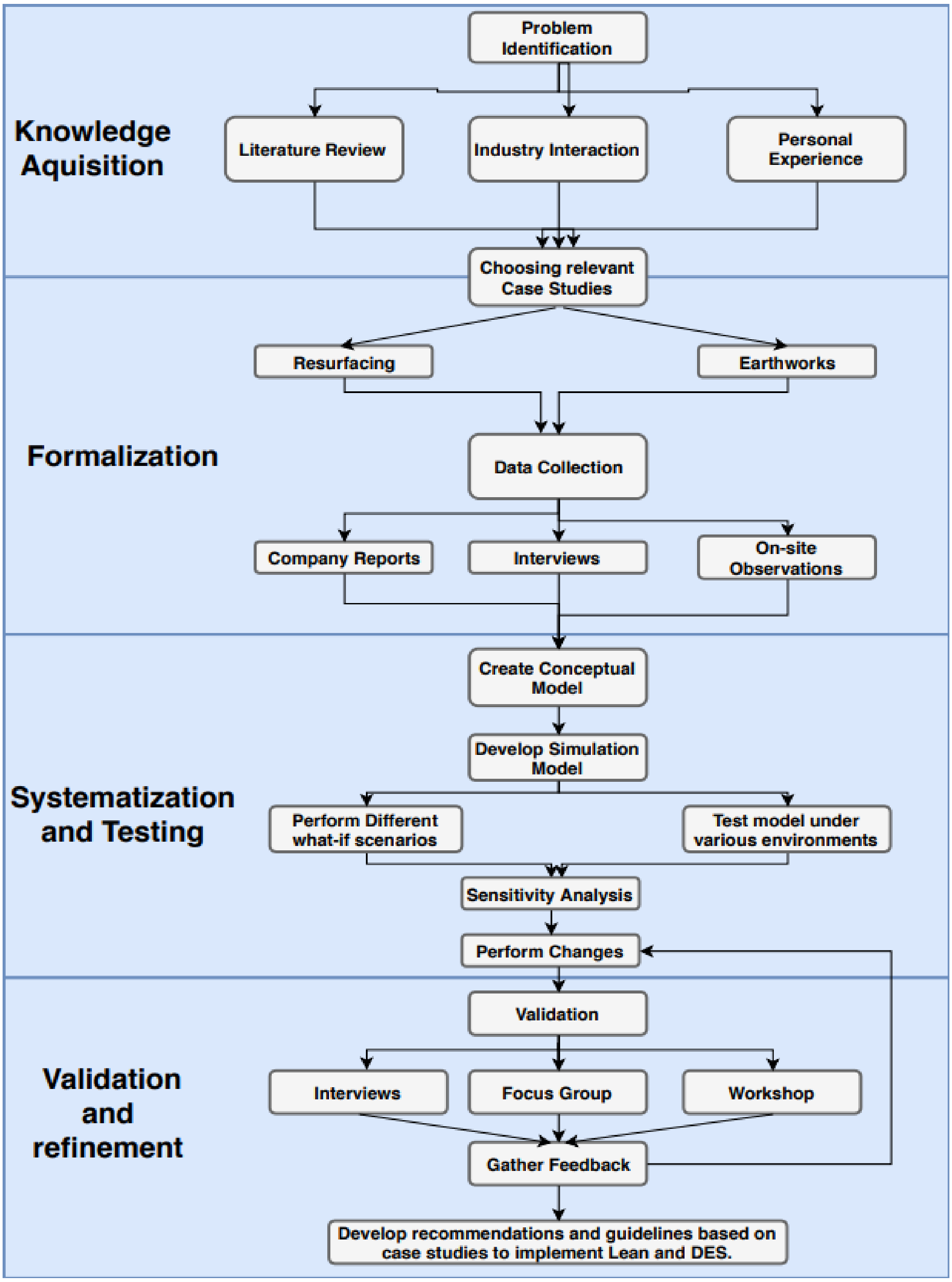


Figure 3.3 Various stages of this research work.

Figure 3.3 above shows the methodology of this research work visualised in a step by step manner. The first part of this research is knowledge acquisition which deals with literature review about the highways sector and finding relevant data about the optimisation theories in practice. It will demonstrate the challenges faced by the highways sector; current problems faced the construction industry in terms of productivity, and manual-based improvement techniques and then finally computer-aided simulation methods. This will set the theme and demonstrate the need for using such approaches and how they can prove beneficial in the highways sector around the world. The results of this section will help in presenting a summary of the current situation and the requirements of future.

The second stage is called formalisations stage where two separate pilot projects are performed using Highways England's projects in the UK. The literature review and industry interactions are based on action research approach where the researcher works in close collaboration with industry participants to understand the problem in detail and then jump for the solution stage.

The third stage is systemization and testing. In this step, a conceptual model is created which then leads to actual model creation after verifications. After that, simulation modelling will be used to simulate the as-is situation of two different operations (resurfacing and earthworks). After modelling, various tests can be performed in the computer environment to find the best scenarios and then the results are verified and validated by demonstrating to experts and make any suggested modifications in the model.

Validation is the 4th stage of research. Lastly, the fourth stage is validation and refinement where a researcher arranges interviews, workshops, focus groups to verify and validate the findings of his or her research and gather feedback on the working of artefact and how it can be made better.

3.4 Constructive Research vs Other Research approaches

Constructive Research Approach is a type of applied study, which intends to develop new knowledge as a normative application. It means that the results of this method should express how one should act in a current situation to achieve the desired state (Kasanen et al., 1993). Hence, there is an assumption about the causation of few things; to recommend action for resolving a problematic state, there is an assumption that the recommended action will cause some expected effects. Presenting such technical norms without assumption would be unscientific. Therefore, it is this normative character and the quest of change in reality that discriminates constructive research methodology from other field research categories and primary type or less empirical types of research (Pasian, 2015).

This approach can be stated as a kind of field research parallel to similar case research, grounded theory, theory testing case research, ethnographic research and action research (Lukka, 2003). Action research is usually considered similar to constructive research; however, it differs in three significant ways. Firstly, the focus of constructive research is always to develop a construct (solution) as a result, while action research may have other objectives. Secondly, the researcher's interaction with industry and practitioners is standard and not obligatory as in the case of action research. Lastly, the researcher's work will not directly influence an individual's thinking as sometimes noticed in action research (Dave, 2013).

3.5 Need for the Design Science Approach

Design Science and constructive research approach not only deal with real-world problems that are practical but also consider its theoretical contributions. It thus links academic and research environment with industrial complications to propose a solution (Hevner et al., 2004; Lukka, 2003). This approach also improves the significance of the problem or in other words, the tone of a research problem in some areas.

It has been noticed that methods like surveys, interviews and observations lead to weak and vague results in research areas that deal with practical problems or are close to industry. One reason is the lack of expert knowledge about a particular issue in the audience of surveys or interviews. Another aspect is the frustration found in the industry due to frequent requests for participation in voluntary interviews and surveys (Kasanen et al., 1993; Lukka, 2003). However, in constructive research there is two-way communication between researcher and organisations and groups also get some knowledge and solutions in return.

The issue of relevancy gap has plagued the academic research primarily in the information system and management areas. Design science provides an adequate method of addressing this challenge. Natural science investigation techniques are suitable to study emergent and existing phenomena. However, these methods are inadequate to investigate tricky organisation problems that require novel, innovative and creative solutions. These particular type of issues are better addressed using a kind of paradigm shift offered by design science (Hevner and Chatterjee, 2010).

3.6 Process of constructive research

Every research approach and methodology follows a list of rules and stepwise procedures to achieve the desired results. This ensures that each aspect of the problem is investigated appropriately and no component has been missed. Constructive Research or Design Science also follows a 7-step procedure from finding a problem to validate the solution. Each cell in the picture below has a specific objective and utilise different methods to achieve it. Lukka (2003) has provided a list of steps to be followed that are shown in Figure 3.4 below and explained briefly after it.

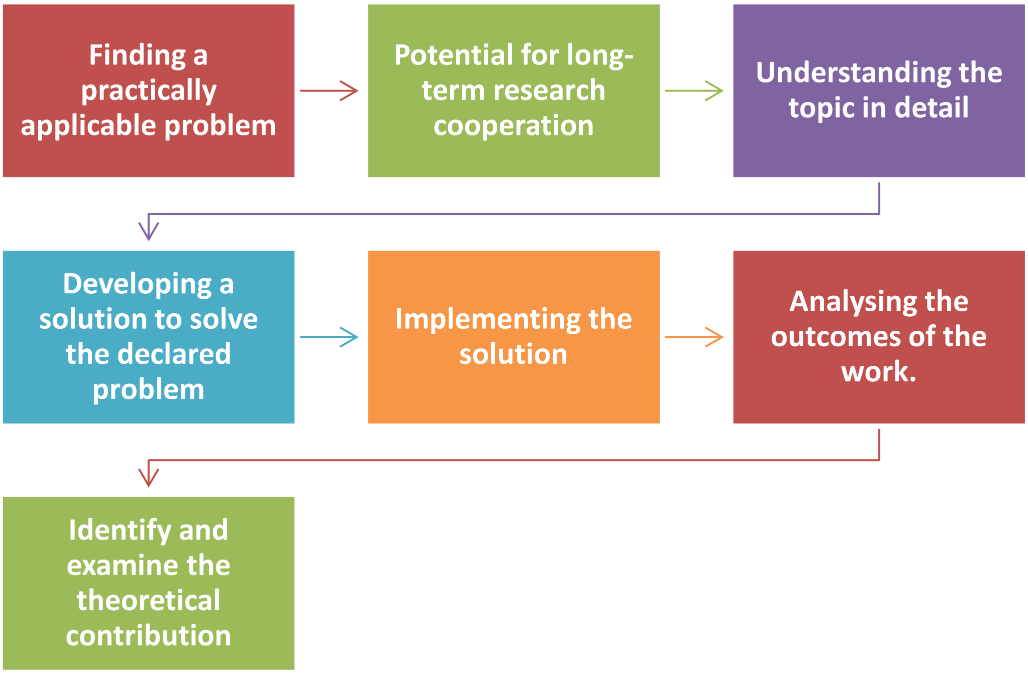


Figure 3.4 Steps taken in design science research, Lukka, (2003).

3.6.1 Finding a practically applicable problem

The first step is to search a practically relevant problem that also possesses the potential for some theoretical contribution. Usually, it is chosen from the researcher's personal experience, i.e. by working in the industry and personal observations, etc. However, it is not a standard practice, and people also find it helpful to discuss with experts in the field after they have identified a research gap before they make a final decision (Dave, 2013). A practically related problem can also be determined by discussing with experts, practitioners, literature review, personal observations and experiences. If a literature review is used as a primary source, it is a good practice to review industry journals and similar sources. To summarise, a research problem should have both the theoretical and practical contribution.

The problem in this particular case is related to construction productivity in general and highways sector in particular. The researcher's personal experience, interaction with industry experts and literature review about construction productivity demonstrate that a significant amount of savings can be made if some recurring construction operations are improved. Highways sector has similar demands around the globe, and the solutions developed in one place can be applied to other as well. In this way, it will have both the contributions to the theory of optimization as well as practice.

3.6.2 The potential for long-term research cooperation

The fundamental idea of design science or constructive research is to solve an industry-related problem. Therefore, before initiating the research process, it is necessary that the researcher has a healthy relationship with the targeted organisation. Generally, the input is required from both the academic and industrial partners, and it should be clearly stated before starting. The researcher and its institution have an excellent relationship with the Highways department in England, and they have been collaborating together for the last few years on different projects. This makes it easier for both parties to understand each other and collect relevant information when required.

It is an excellent opportunity for industry participants to collaborate with academia and to learn from their knowledge and expertise. Constructive research connects research and practice in a better way and also increases the significance of academic construction management (AlSehaimi, 2012). To avoid any issues in future, some key milestones, research activities and funding issues (if funded research) can be stated at the beginning of investigation work.

Understanding the topic in detail

The primary purpose here is to describe the research area, and it’s the current situation in detail before going towards a solution finding stage. One of the most important measures in this methodology is to understand the research question in in-depth detail. At this step, a researcher usually contacts industry experts, organise interviews, perform direct observations or analyse the current literature to understand the research gap fully. If a researcher is not well-informed about the current theories and practices, he/she will not be able to analyse the outcome of the investigation and how it contributes to the existing theories in this area.

Usually, it is done by analysing the literature review, but sometimes there might be no published material about the problem. However, the industry collaboration and personal experience help a lot at this stage. At this point, it acts like action research where the researcher comes from practice with a defined problem. However, in design science, a researcher goes from academia to practice, finds a problem and brings it back to create a solution.

Developing a solution to solve the declared problem

Developing the solution is the heart of the research work performed. It is the most formative stage in the research where a researcher has to design the final shape of a solution. Usually, an iterative (trial and error) procedure is used to generate a solution and this itself is a considerably valuable contribution to knowledge. At this stage, a researcher develops a conceptual solution to address a previously identified problem. If the researcher is working with partners in practice, they might also suggest some possible solutions which can be very helpful. As the experts in the industry understand the problem in detail, sometimes, they are also aware of the possible solution but are unsure of the possible outcomes.

A conceptual solution should also address the surrounding issues that are found during the research and ensure the applicability of the developed solution. If a model or framework has been established that cannot be implemented, it does not fulfil the criteria of design science. At this stage, a researcher identifies the opportunity to create a solution and if it is not possible, particular changes are made in the research. A solution can be a set of recommendations, a framework to facilitate implementation or a simulation model etc. In this particular case, two simulation models are constructed which will then lead to two different sets of recommendations and finally, a framework can be developed at that stage to implement the findings of this research in industry.

Implementing the solution

The solution or the construct which is created in the above steps cannot always be applied in real life to assess its applicability. This examines the established answer from technical and methodology perspective. The researcher is fully engaged at this stage because they have designed the solution and is the experts in it. This trait of CRA or DS distinguished it from traditional research methods where the researcher hardly collaborates with the industry participants and gathers data personally.

After the construct or artefact has been demonstrated to the experts and is validated, it can be applied in a real life case to assess its feasibility. However, it is not always possible. The simulation modelling proves quite useful here. The models are built using real life data, and it becomes tough for the companies to dismiss the potential benefits of the simulation model.

Analysing the outcomes of the work.

It is the analysis stage where the researcher and partner organisation begin to analyse the results of the implemented solution. There will be many lessons learnt at this stage, regardless of the success of the designed solution. The implementation process is typically hard, and many constraints can be noted down at that stage. If the developed solution is successful, it can act as a Best practice which can then be replicated on the broader industry using the same process steps.

Once a simulation model has been developed, it is verified and validated by focus groups where the experts of simulation and the research sector are present. They comment on the findings of the work and give appropriate feedback. The feedback is then fed back into the simulation modelling (as minor modifications), which increases its strength and reliability.

Identify and examine the theoretical contribution

This step is the most significant part of research from an academic and research view. At this stage, the researcher reviews the results of the implemented solution. There are two different types of contributions of the research for the existing theory, the new construction (solution of the problem) and the positive relations behind it (Lukka, 2003). If the newly designed solution is satisfactory or not, it will still be a contribution to the current theory itself due to the nature of this work.

Figure 3.5 below by Hanid, (2014) demonstrates an excellent visual to summarize the process of a design science or constructive research approach and the relationship between a research process and research techniques and how they are all linked to each other.

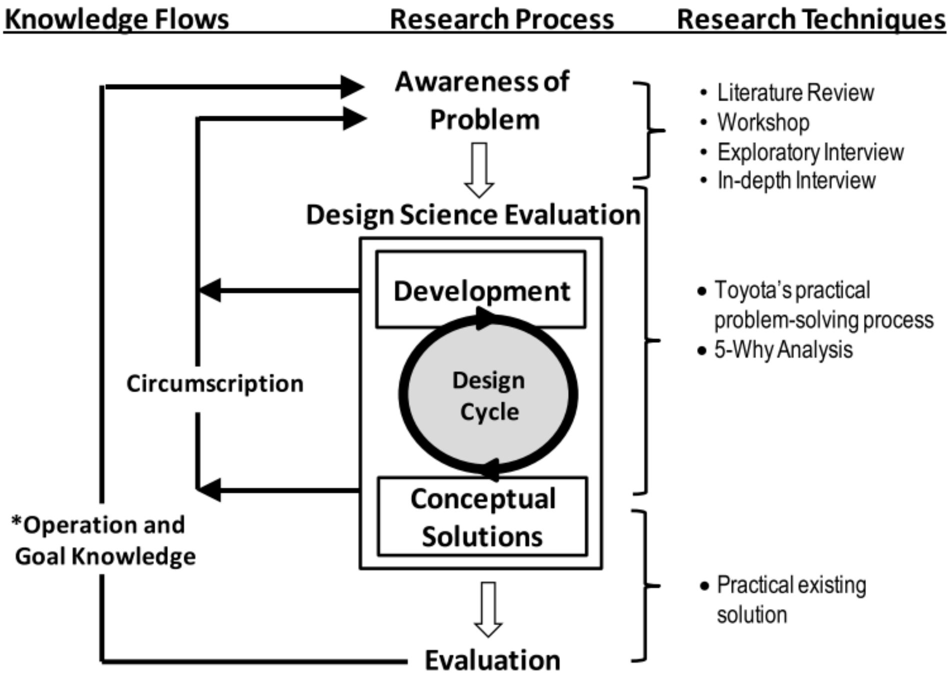


Figure 3.5 Relationship between research process and techniques, Hanid,(2014)

3.7 Validation of Artefact

Once an artefact of any sort has been developed, it is essential to verify and validate it. The two case studies will develop two artefacts eventually, which will be the simulation models and their guidelines. Before finalising the work or making bold statements, it is critical to assess and validate the artefacts. If the artefacts are not verified and validated, they basically have no value and contribution. For this purpose, this research work will incorporate two different types of validation processes to assess its robustness, validity, performance, accuracy and relevancy efficiency.

These two validations are:

1) Theoretical testing.
2) Focus Group.

3.7.1 Validation by Theoretical Testing

Design artefacts can be considered as systems and can be characterised in terms of goals, factions and adaptation. The structure of the artefact should also be distinguished from the environment (in which it operates) for enhanced understanding. In this manner, the artefact will possess all dimensions of the canonical form of a system (Simon, 1997). Prat, Comyn-Wattiau and Akoka, (2014) developed a robust hierarchical criterion to validate a design science artefact theoretically. They profoundly reviewed the relevant literature and then adopted a systemic approach to creating this hierarchy by embracing the procedure for taxonomy development proposed by (Nickerson, Varshney and Muntermann, 2013).

Figure 3.6 below shows the hierarchal validation model developed by (Prat, Comyn-Wattiau and Akoka, 2014) which looks at a system's or artefact's dimensions like its goal, environment within which it operates, its structure, activity and evolution.

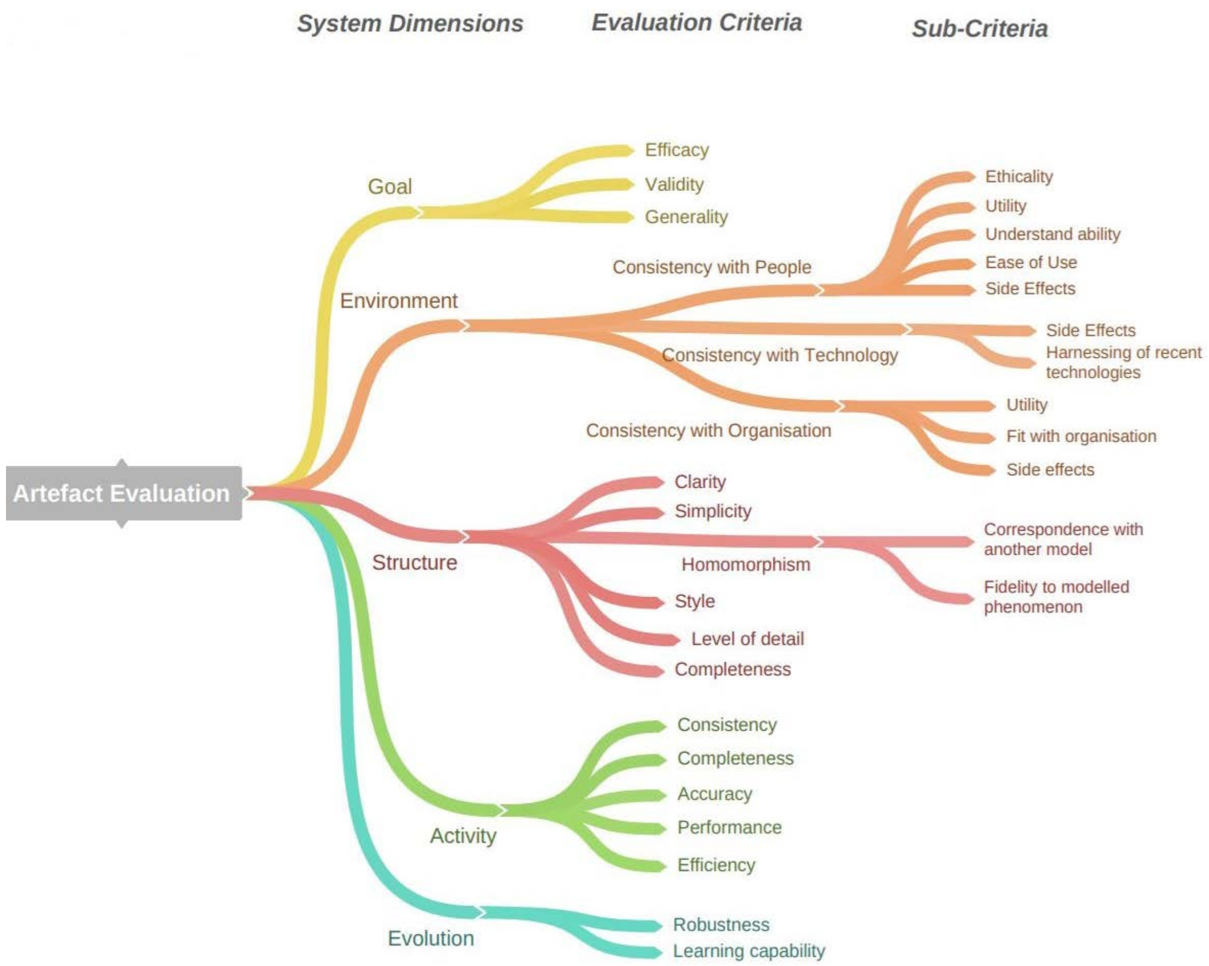


Figure 3.6 Hierarchy of Criteria for Artefact Evaluation, Prat, Comyn-Wattiau and Akoka, (2014)

The evaluation criterion is much more detailed and looks deep into factors like validity, generality, consistency within people, organisation and technology, completeness, simplicity, homomorphism, accuracy, robustness and ability to learn etc.

Design artefacts can be considered as systems, and these systems have five dimensions as characterised by Prat *et al.,* (2014). These five dimensions are:

Goal.

A goal describes the purpose of developing an artefact and how useful it is. Its effectiveness, validity and generality can characterise it. Efficacy is the extent to which an artefact achieves its goal or produces its aspired outcome (Venable, Pries-Heje and Baskerville, 2012). The term efficacy is used as it's the more commonly used term. Similarly, validity is the extent to which an artefact works accurately, i.e. accomplish its goal correctly, and validity incorporates reliability (Straub, Boudreau and Gefen, 2004; Gregor and Hevner, 2013). Artefact generality is the generality of its purpose, the broader the purpose addressed by the artefact, the more general the artefact will be (Aier and Fischer, 2011).

Environment.

The business environment dimensions include organisation, technology and people (Hevner *et al.*, 2004). Hence, the criteria for this dimension should test the consistency of artefact with organisation, technology and people. Consistency can be defined as the harmony of features to one another or a whole. Regarding organisation, it determines the quality of an artefact in practical use. Its utility does not necessarily unfold into utility for the whole organisation. For people, it's the ease of use, understandability and ethicality of an artefact which relates (March and Smith, 1995; Venable, Pries-Heje and Baskerville, 2012). If an artefact fits well with the organisation, it satisfies the organisational environment check box. At this point, both its advantages and disadvantages should be considered in its environment.

Structure

The structure of an artefact is determined by its simplicity, completeness, style, clarity, level of detail, homomorphism and consistency. According to Smith, Osborne and Forde, (1995), consistency, level of detail, completeness and persistence are required criteria for a model.

Here the uniformity of structure means internal uniformity. Simplicity and clarity are important factors because an artefact will be of no use to the majority of users if it lacks these features. A homomorphism is the communication of a model with another model. It can also be explained as the closeness of a model to modelled process. It is not usually specified as a criterion in the research; however, it matters a lot as it relates to the construct redundancy, overland, deficit and excess (Wand and Weber, 1993; Siau and Rossi, 2011).

Activity

Activity can be defined by its accuracy, performance, completeness, consistency and efficiency. Accuracy is confirmed when there is a specific agreement with the results of current trials (Aier and Fischer, 2011). Accuracy and performance are considered as a necessary criterion by Hevner *et al.*, (2004). If an artefact is not accurate and doesn't perform as required, it fails the rest of the tests as well and is not fit for the purpose. Completeness amounts to the functionality and consistency refers to the static and dynamic features of artefacts.

Evolution

Learning capability and robustness can describe the dimension of evolution (Prat, Comyn-Wattiau and Akoka, 2014). Robustness is the ability to respond to the variations of the situation. For instance, a simulation model has to be tested under various conditions to see if it will adopt the changes or will fail if ideal conditions are not met. Learning ability is the skill of a system to learn from its encounters and the reactions of the situation.

3.7.2 Validation by Focus Group

Focus group discussion is frequently used as a qualitative approach to gain an in-depth understanding of an issue (O.Nyumba *et al.*, 2018). Focus groups began in group therapy and were based on the theory that individuals who share a common concern will be more amenable to discuss it in combined sessions compared to individual interviews, thereby extracting opinions that would not otherwise appear in one to one interviews (Lederman, 1990). In this method, participants can answer, confront and analyse each other's ideas which cultivate reliable rather than socially acceptable responses (Kidd and Parshall, 2000). It also results in more than the sum of what participants would give as individuals (Osborne and Collins, 2001). Focus groups have been used by sociologists and psychologists for well over half a century, but it is only in the last decade that they have become a prevalent and favourite method for many (Wilkinson, 1998).

Focus groups not only provide an opportunity to question each other's opinions, but it also allows participants to re-evaluate and revise their own views as well (Gibbs, 1997). They enable complicated issues to be explored in more detail, and more data can be collected in limited time as compared to individual interviews because a question is asked only once and then all respondents answer it gradually moving to the next one. However, in one-to-one interviews, all the questions have to be repeated one by one (Lederman, 1990). It also allows more people to be involved in minimising the inconvenience for the participants and the researcher. Focus groups assist people in learning more about the group or community needs and opinions. In this manner, they can are analogous to needs assessment surveys (Berkowitz, 2016), however, focus groups are typically spoken, relatively broad, qualitative and open-ended as compared to needs assessment surveys which are closed-ended, written and quantitatively scored.

It is sometimes mentioned that the group dynamics can have unintended effects on some participants. However, it can be mitigated by the researcher’s ability to intervene and avoid random topics (Jarrett, 2013). Furthermore, the design of questions will allow the researcher to obtain quality data even if some participants were affected by other’s opinions. It is a good idea to capture more data on paper than relying on audio recordings as it is hard to determine later on due to the mixing of voices. To avoid these issues, the author developed semi-structured questions along with rating tables where participants can insert their comments and can give ratings of the desired item.

There are several opinions about the number of participants and their effects. According to (Rabiee, 2004), the number of participants depends on the type of research. For large scale, quantitative survey the researcher will need to contact much more people than you would for a small qualitative piece of research. The sample size will also depend on what a person wants to do with the results. If the researcher intends to produce large amounts of cross-tabulation, the more people they contact, the better (Pearson and Vossler, 2016).

Usually, there is no simple answer to decide how much is enough in terms of sample size for a focus group is. In a case study, the sample size is often tiny and therefore, purposive sampling is used (Saunders, Lewis and Thornhill, 2007). The sample size depends on the level of consensus (Guest et al., 2006). Rabiee, (2004) argues that ideally there should be six to ten participants, whereas Osborne and Collins, (2001) claim that a group of between four and twelve is practical. It is a widespread belief view that participants should not know each other (Lederman, 1990) which is not always possible. However, in this particular case, the author was fortunate enough to find participants who were all very experience but did not know each other well. Focus groups usually last for one to two hours (Gibbs, 1997). For this research work, it lasted for about one hour each for one case study and took roughly two hours in total for both.

For this particular research, it was intended to have 7-9 experts / industry people for focus groups after both models were developed in discrete event simulation. They would be chosen based on their experience in industry and knowledge about simulation and productivity improvement methodologies. The researcher aims to have two different case studies that are based on real life projects and are performed in the United Kingdom. It means that 7-9 people will be contacted after these case studies have been studied and their computer-based model have been developed, and then needed validation. The more realistic option is to develop both models and then perform the validation of both in one go. Since the scope of work and nature of case studies is not different from each other, participants will be able to contribute positively.

The researcher intends to invite at least 1 person from Engineering side, 1 from Planning, 1 from accounting and finance, 1 from lean and last 1 from project management. Due to the mixture of experts, this can be an ideal situation, and in this scenario, each person will contribute to the DES model, its advantage, its technical construction and future uses and their perspective which will be different from others but equally useful for the researcher. It is not necessary for them to have the expert knowledge about DES, they will look at the benefits realised by the what-if scenarios performed by DES and comment on it. They will also help in telling whether these what-if scenarios are practical or not and how they can be improved further.

There are some situations where one person holds enough experience to answer questions from engineering, finance and planning side. For instance, a Project Manager has been involved in a project from the beginning and knows about the planning stage, the PM manages the construction and understand the engineering principles very well and also looks after the spending of resources. If a project manager is available, then 5-7 interviewees will be enough as well to comment on the DES model and its implications and how it can be taken any further. Therefore, first preference will be to contact Project Managers in advance and carry out the interview with them. They will be equally interested in the work as it is action research and is based on an industry based problem and its results will help them as well in return.

According to Lederman (1990), Semi-structured focus group interviews involve a variable amount of prompting. Usually, open-ended questions are asked at the start to diminish an undue influence on participants' thinking. Follow up questions are asked carefully by the researcher while keeping the influence minimum. It is, in fact, the research who will decide to follow up on a particular question and will ignore the inappropriate responses. Therefore Gibbs (1997) has listed few guidelines for the focus group moderators which are:

- Explicitly describe the purpose of research and interview that will put them at ease.
- Keep the communication relevant.
- Ask open questions, object participants and inquire for details.
- Avoid giving too many opinions or approvals.
- Ensure everyone gets a fair chance to contribute.

The data obtained from the interviewees will be fed back into the simulation model in two forms. Firstly, their responses will validate the findings of the created simulation model by the researcher. They will perform a critical analysis of the model and will point out any shortcomings. Secondly, the information received from them will further enhance the strength of the model as there are few assumptions in any simulation model which can only be verified by an expert.

More than ten experts were carefully invited for the focus groups to validate the findings of the simulation models developed during this research work. 7 of them agreed to participate in the workshop and out them 3 people were lean managers, 2 were project planners and rest 2 were BIM and IT in construction specialists. All of them had higher education in the respective area and at least more than 5-6 years of experience in the field of construction and highways maintenance. Most of them agreed that Discrete Event Simulation is underutilised in the construction sector and the integration of lean and simulation is quite rare in this regard. However, this combination of optimisation methods can save millions of pounds wasted during the inefficient operations. Most of the experts were aware of this particular simulation technique and had heard of it or used it before at some point.

Before the focus group, participants were provided with all necessary information including the background of the project, current challenges, developed solutions and its benefits. At the same time, they were presented with a consent form, withdrawal form, interview guide, interview questions and confidentiality issues. They were ensured about the anonymity and confidentiality concerns, and they felt comfortable throughout the focus group workshop.
The data obtained from the focus group was utilised in two different ways:

1) It helped to verify and validate the correct functionality of the artefacts (simulation models) and confirmed that they could be used in other projects too. It also approved the integration of lean and discrete event simulation and how this combination can be further improved.

2) Some of the scenarios were modified accordingly after the feedback from the participants. Some scenarios were too idealistic and could not have been implemented in a real life situation.

The participants were welcomed and briefed about the nature and scope of research and why they were chosen for the discussion. They were informed of the basic rules of focus groups discussion, the role of moderator, facilitator and the audio recording of the session. It was explained that there is no right or wrong answer and the researcher will benefit from all sorts of responses in some way or another. The study was presented as the independent research of the author to avoid any bias towards the organisation or funders etc. The process of this particular focus group was conducted as:

1) General Introduction towards the problem of productivity and construction sector and how the UK's construction is underperforming compared to other developed countries.
2) Briefing about Case Study 1, (Roads Resurfacing) demonstrating its simulation model, how it was developed and tested, what experiments were performed and why, and what functions does it have, e.g. flexibility, generalness, adaptability, ability to learn etc.
3) Briefing about Case Study 2, (Earthworks optimisation) demonstrating its simulation model, how it was developed and tested, what experiments were performed and why, and what functions does it have, e.g. flexibility, generalness, adaptability, ability to learn etc.
4) Data collection through a semi-structured questionnaire developed specially for this research (Attached in Appendix 4) to capture participants responses and feedback. It was a combination of open and closed-end questions multiple category questions, factual statements and rating scales to obtain scores. Participants were given interview guides beforehand, and the data was collected at this stage of a focus group workshop. This data was used to test the efficiency, reliability and accuracy of the artefacts by looking deep into its strengths and weaknesses.
5) Debriefing session to appreciate and regard the valuable feedback captured from the participants. They were told how it would benefit the simulation models and the researcher as well.
6) Data analysis was performed, and a summary of the responses was prepared which is listed in each case study section.

The questions were asked, responses were recorded and then analysed. During the opening questions session, participants were asked about the overall application of Discrete Event simulation, its usage in Highways, its comparison with other tools and its integration with manual approached like lean etc. Their responses are recorded in the graph on the next page in Figure 3.7. Most of the participants agreed with the research problem of this research work that Simulation techniques have been underutilised in the Highways sector. They also strongly agreed about the strengths of discrete event simulation modelling, its ability to model most resources and constraints reduce uncertainty and perform better than the manual techniques.

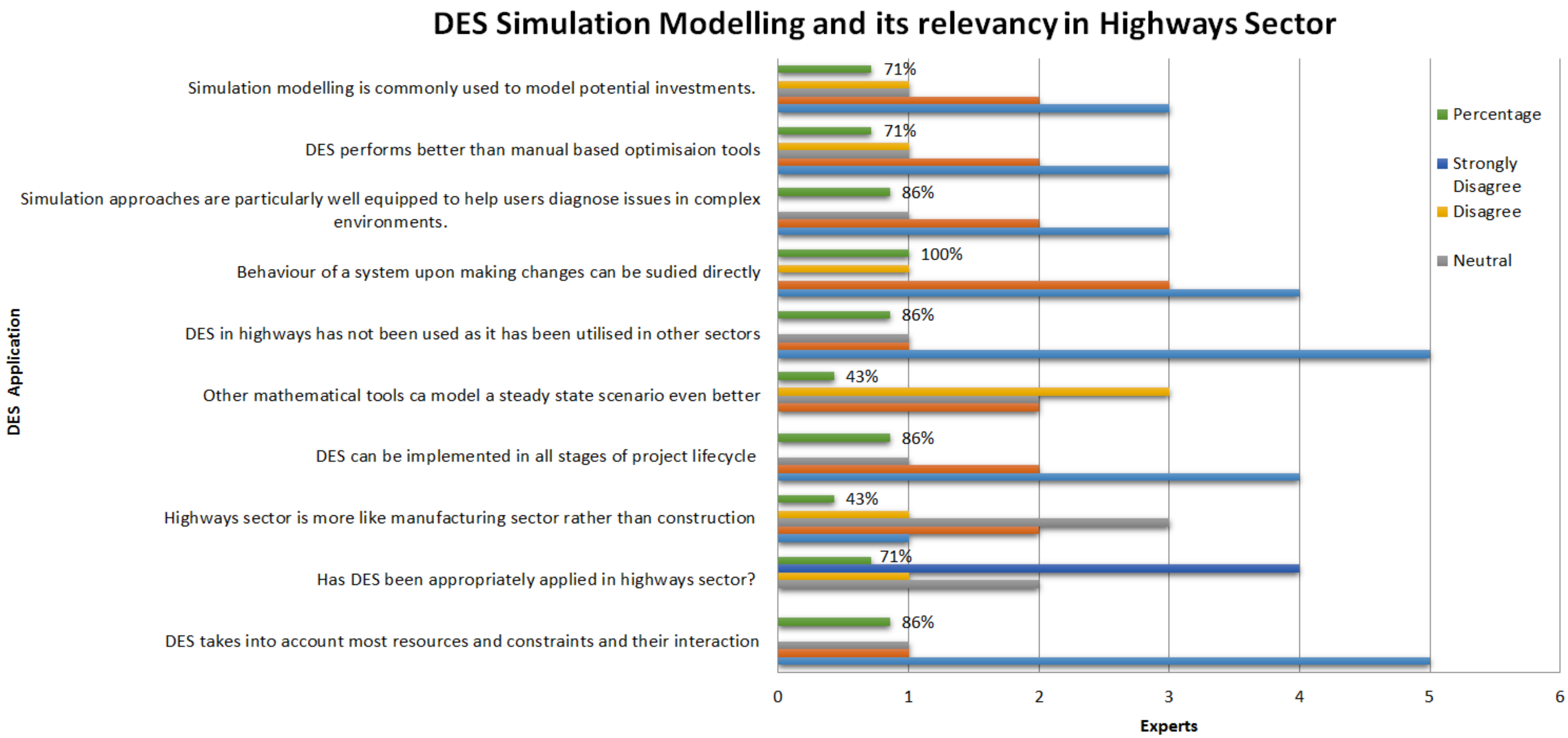


Figure 3.7 Response of Focus group about DES simulation modelling and its relevancy in Highways Sector.

Simulation modelling has been used in construction processes and is regarded as a reliable tool in project management (Gowda, Singh and Connolly, 1998). It is due to its strengths in strong visualisation abilities, future planning modules, clash detection features and the ability to perform various what-if scenarios that are otherwise not possible in real-life cases most of the times. These experimental scenarios can also reduce risk to a great extent. Figure 3.8 below shows the response of participants captured during the workshop about the question of simulation medalling's strengths. Most of the participants agreed that the what-if scenarios ability is the most robust feature of simulation modelling and this cannot be performed using manual techniques accurately.

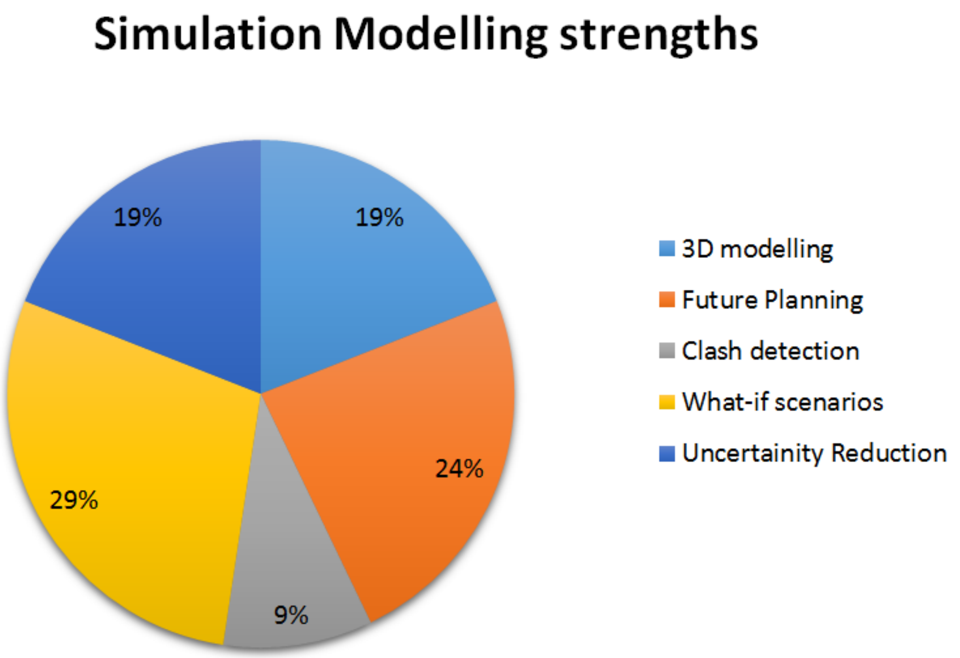


Figure 3.8 Responses of focus group about the strengths of Simulation modelling.

There are three paradigms of simulation modelling; however, discrete event simulation is most relevant to the as-is situation analysis at the macro level. The participants were asked about its applicability in the construction sector, whether it can be applied to most of the building processes in real-life.

Figure 3.9 below shows the responses of participants about the applicability of this technique. Majority of participants (43%) agreed that these models apply to real life and the rest of them agreed on a condition that the experts should approve the model after development.

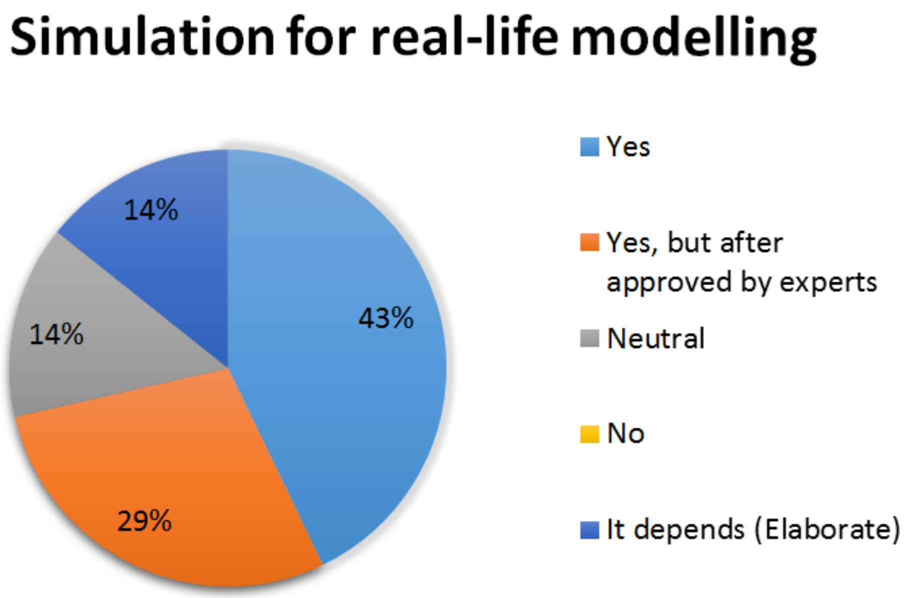


Figure 3.9 Responses of a focus group about the applicability of simulation modelling in real-life.

Two of the case studies were then evaluated one by one to make sure that the developed artefacts are practical, efficient and can be used in real life on other projects or locations etc. The validation of the 1st case study, Resurfacing optimisation is performed in section 4.6.2 Validation from a focus group of experts. The validation of the 2nd case study, Improving Earthworks is shown in section 5.6.2 Validation from a focus group of experts.

3.8 Summary of Chapter 3

There is always room for improvement in any industry at any time. Since the construction sector is enormous and complex, the efforts to improve it should be rigorous and comprehensive too. The purpose of this research is to improve the productivity of highways construction processes using Simulation techniques to experiment with various situations in a computer-based environment and develop a framework to implement these findings back into highways sector. The constructive research approach is adopted to create a solution, which will solve a practically relevant problem and also contribute to theory when fully implemented and tested.

3.9 Case Studies

In the design science and constructive research methodology, the researcher starts with a practical problem, explores it further to gain in-depth knowledge about it and then creates a solution or construct to overcome the initial problem (Dave, 2013). This research looks at improving maintenance and construction operations within the highways sector using the integration of lean and discrete event simulation.

Two different case studies have been chosen so far for this research. Obtaining the desired number of case studies is not under the control of the researcher and depends on various factors like availability, geographical constraints, data protection issues, etc. The two case studies chosen in this investigation are all of the different nature and are treated in a similar manner to demonstrate that simulation can prove helpful in all sorts of construction and maintenance operations. The list of the cases is:

1. Enhancing resurfacing procedures. Case Study 1, Chapter 4

2. Improving earthworks operations. Case Study 2, Chapter 5

All these case studies are chosen within the United Kingdom and are related to Highways sector within England. They mark different stages of roadworks that are carried out every day in various parts of the country. Figure 4.0 below displays several methods that were used to understand the problem in detail, collect data from the highways agencies and other stakeholders involved and then analysing it using various techniques. All two case studies followed a similar procedure, and almost same steps were repeated each time.

Figure 4.0 Various measures taken during the research to complete the case studies, Qasim et al. (2017).

Chapter 4 : Case Study 1 Resurfacing with Discrete Event Simulation and Lean

Sections

4.1	4.2	4.3	4.4	4.5	4.6
Background of case study	Knowledge acquisition stage	Formalisation stage	Systemization and testing stage	Validation and refinement stage	Documentation and Implementation stage

This section presents a case study of resurfacing which is called “1000 tone trial”. It was a joint venture performed by the highways agency, resourcing and other contractors’ responsible for white lining and traffic management. The motivation was to maximise the production each night and achieve maximum results. They managed to reach high results and productivity was also increased using traditional lean approaches. The data was stored with Highways England and was obtained from them by the researcher for research purpose and to improve it even further.

Resurfacing is a maintenance and preservation operation where a thin layer of the road is shaved off from the top surface, treated, and then a new layer of asphalt is placed above it (MPA, 2009). This is a standard procedure and is performed all over the world every day. Resurfacing increases the strength of the road and extends its life. It improves the riding quality and water drainage and restores the aesthetic appearance and skid resistance of the old sections of a road.

4.1 Background

The demand for road maintenance, preservation, extension and resurfacing is continuously increasing and the time slots available for these works is getting tighter and tighter (Marzouk et al. 2011). The resurfacing and rehabilitation of road pavements have become an expensive necessity, due primarily to the enormous volume of commercial and private vehicles using the roads, which cause roadways to crumble rapidly and makes their repair challenging to carry out.

New infrastructure and congestion relief projects can be delayed and are usually delayed due to various reasons, mainly financial problems. However, maintenance (resurfacing, rehabilitation, etc.) projects cannot be postponed as they directly affect the road network. As soon as a road is built, it starts deteriorating due to many causes like weather, traffic and quality of materials (Department for Transport, 2013). It is a common phenomenon worldwide, and its appropriate mitigation is necessary. Even in a developed country like the USA, 32% of roads are in poor or mediocre condition, and motorists are paying $67 billion per annum in operating and repairing costs (ASCE, 2013). Without appropriate rehabilitation, these structures will eventually collapse causing an even more significant challenge for traffic (Christory et al., 2008).

According to Department for Transport (2016), the United Kingdom's government aims to spend £3 billion to support local transport projects by 2021 and has planned an investment of £11 billion of capital expenditure to maintain, operate and improve 4,000 miles of the strategic road network. After the funds have been granted, it is necessary to improve the current practices, especially the maintenance processes, to utilise the money in the most efficient way.

UK Government has announced a £1 billion budget per year for maintenance projects throughout the network (Department for Transport, 2015). Though, the most significant demand is to improve the maintenance projects to utilise the money in the most efficient manner and deliver quality. Construction productivity has been on a decline for decades and maintenance activities had the same performance (UKIPR, 2015).

4.2 Knowledge Acquisition Stage

Road maintenance affects all aspects of performance – the time that roads are affected by repairs directly impact on accidents, vehicular emissions and road user satisfaction (DFT 2015). Within the UK, "Highways England" responsible for maintaining, operating and improving over 4000 miles of the strategic road network. It is in charge of carrying out bulk quantities (80% of the system) of re-surfacing operations over 5 years 2015-2020, whilst keeping 97% of the network free of Traffic Management at any point in time (DfT 2016, ORR 2015).

In the first quarter of 2015, the output of roadworks, as part of infrastructure works, reached up to £1,115 million (ONS 2015). Such output forms about 26.3 per cent of infrastructure work and 5.4 per cent of all new construction work (Aziz, Qasim and Wajdi, 2017). There is an obvious need for cost-effective maintenance that minimises the occurrence and duration of disruptions resulting from roadworks. Furthermore, it is becoming vital to delivering major road schemes in resource-constrained environments, while maintaining safety, cost efficiency, sustainability and minimal impact on road users. Figure 4.1 below shows the national infrastructure plan for coming years by the department of transport which highlights their priorities in terms of expenditures.

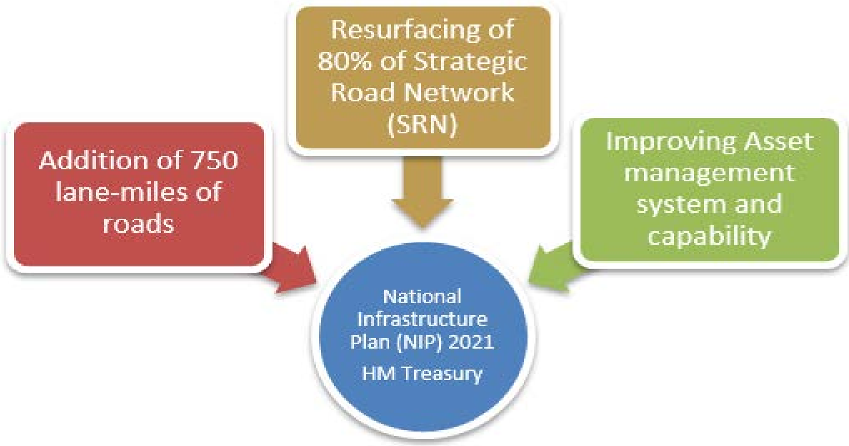


Figure 4.1 National infrastructure plan for 2020-2021 by department of transport.

This particular section of road, used in the case study carried 108556 vehicles per year (2013 data), including 20% Heavy Good Vehicles and required re-surfacing. The motivation of improvement project was to deliver efficiency by maximised output and use of resources, improved utilisation of road space and by benefiting travellers through fewer road closures. There were inefficiencies noticed in the process and due to the incompetent working style of subcontractors, an enormous amount of resources were wasted, and traffic was disrupted on a daily basis (Qasim and Aziz, 2017b). This area is called as Area 9 by Highways England.

The development of Area 9 covers Highways England's road network in Central England. It comprises some significant parts of Shropshire, Staffordshire, Herefordshire, Worcestershire, and Warwickshire, as well as some regions of Derbyshire, Gloucestershire and Leicestershire. It also includes seven metropolitan boroughs of City of Birmingham, Coventry, Dudley, Sandwell, Solihull, Walsall and Wolverhampton. Highways England has to carry out bulk (80% of the network) of resurfacing operations over 5 years whilst keeping 97% of the system free of Traffic Management at any point in time.

The current process of resurfacing has flaws and does not make the best usage of available resources. Figure 4.3 in next section demonstrates the current or as-is process where the equipment and other resources re under-utilized causing in lower output.

4.2.1 Identification of Problem

At this stage, the current or as-is process of resurfacing was studied in this particular case study and various constraints were mapped. It is impossible to improve any process without identifying the issues and problems affecting it. During identification, a collaborative workshop was held at the University of Salford campus where different stakeholders, involved in the resurfacing process were invited. Resurfacing process includes Clients (Highways England), Resurfacing Contractors (responsible for planing and resurfacing operations); white lining contractors, traffic management (TM) companies (usually TM is performed by resurfacing contractor itself) and local council representative, etc.

This 1000 tonnes resurfacing case study was discussed during the workshop. Various process improvement opportunities were considered by stakeholders involved in this work, and it was helpful to have all of them on board to create a holistic approach to the process. Different constraints and potential opportunities were discussed which were recorded. The main aim was to increase the output of the work without changing the working windows or deploying additional resources. This challenge was taken forward, and suggestions provided by the experts were later simulated in the computer-based environment. At this stage, the problem was understood, and a conceptual model was made which would be achieved in the final stages of the work.

4.3 Formalisation Stage

The data required to develop the simulation model was collected from literature review, on-site observations and interviews with the working staff and experts. Highways sector is unique if compared to production of manufacturing industries due to its fragmented nature and number of stakeholders involved. There were several companies improved in the 1000 tonne trial, and it would be a difficult task to obtain data from each of them, and this process could take long time. Highways agency then provided further information about the start of the project, hurdles, faced and their analysis. This data was also used in creating the discrete event simulation model.

The data included excel sheets with details about resources, process maps and their time diaries. Highways England along with their partners managed to explore various opportunities for process improvement and waste minimization were identified covering the full spectrum of activities including motorway closures and planning operations. The work plan was divided into three main steps which included:

- Initially, by allowing an early contact between local traffic control centres, the process was expedited and waiting time for the road clearance process was shortened. It was noticed that material was called off after the operation starts every night and while the material travels from the quarry to the work site, the workforce was sitting idle.

- Secondly, traffic management was set out to close two lanes earlier and bring plant and material ahead of full closure (safety constraints were addressed). This assured that plant and equipment are accessible ahead of the entire road closure. In order to boost the productivity of pavement process, calling stuff earlier would allow paver to begin operations soon. There is a time lag of 14 minutes involved between planer and paver processes to commence, to allow time for cleaning and preparation (Moore *et al.*, 2015; Qasim and Aziz, 2017b).

- The third step was to ensure that work continues close to 6 am – the allocated work window rather than 4:30 am (traditional time). Given the fact that paver utilisation in an average shift is just 33%, doubling pavement productivity by addressing constraints (e.g. earlier mobilisation of the paver, full usage of work window) has the potential to double paver productivity and thus, the output produced. According to Moore (2015), the possibility of extending work windows particularly over weekends or public holidays, when lesser than average traffic volumes are accepted, provided an opportunity to increase working window, which had a direct positive correlation with productivity. It involved increasing the work window to 10 hours and 36 minutes (Qasim and Aziz, 2017b).

During the 1000 tonne trial, the joint team studied all the constraints in detail and tried to map them as well. These limitations were identified using the lean technique of fishbone analysis that helps to outline the factors affecting the productivity of a process (Vertex42, 2013). These factors can then be dealt with in later stages to reduce their impact on the final product or process. In this particular case, 6 Ms have identified that influence the overall project; they are methods, milieu (environment), manpower, materials, machines and measurements. Figure 4.2 below shows the root cause analysis diagram created for the 1st case study during this research work.

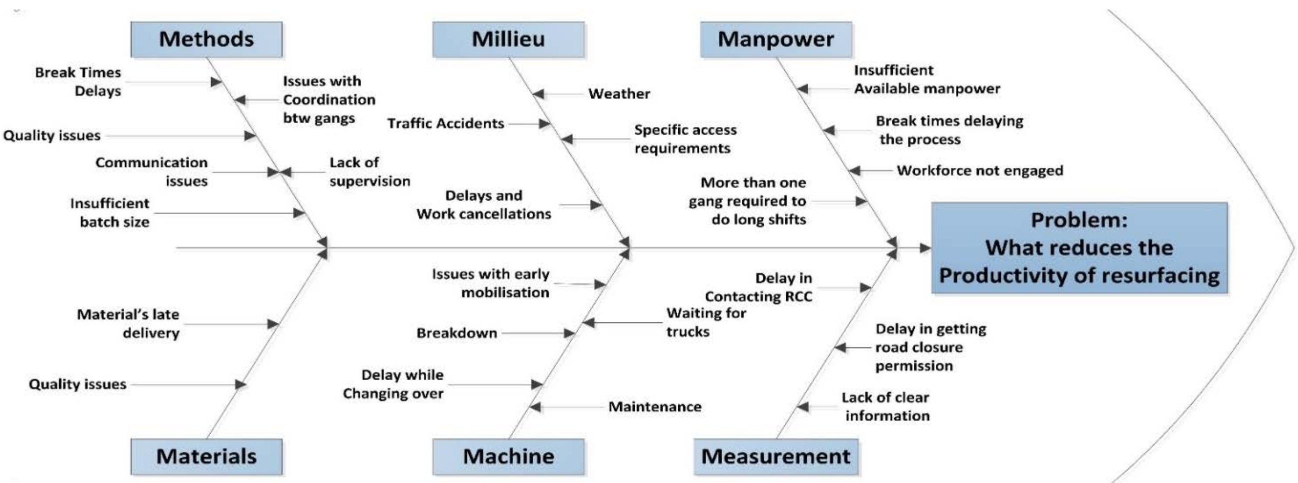


Figure 4.2 Root Cause Analysis of typical resurfacing operation using 6 Ms, Moore *et al.*, (2015).

4.3.1 Before Improvement with Lean

The as-is process was also mapped with respect to time to assess the productivity of each equipment used in the process. This would tell the actual efficiency of each machine and the overall process. Figure 4.3 below shows the as-is process that was performed every day using traditional methods. Archival data was used to map this as-is phase, and the figure was created by Moore et al. (2015), who was leading the team in Figure 4.3. It can be seen that planing operation (removing the top surface of the road) was started at 22:30 even though the work window was available from 22:00. Planing and paving are the main activities in the resurfacing operation, and they were performed for only 30% of the possible time.

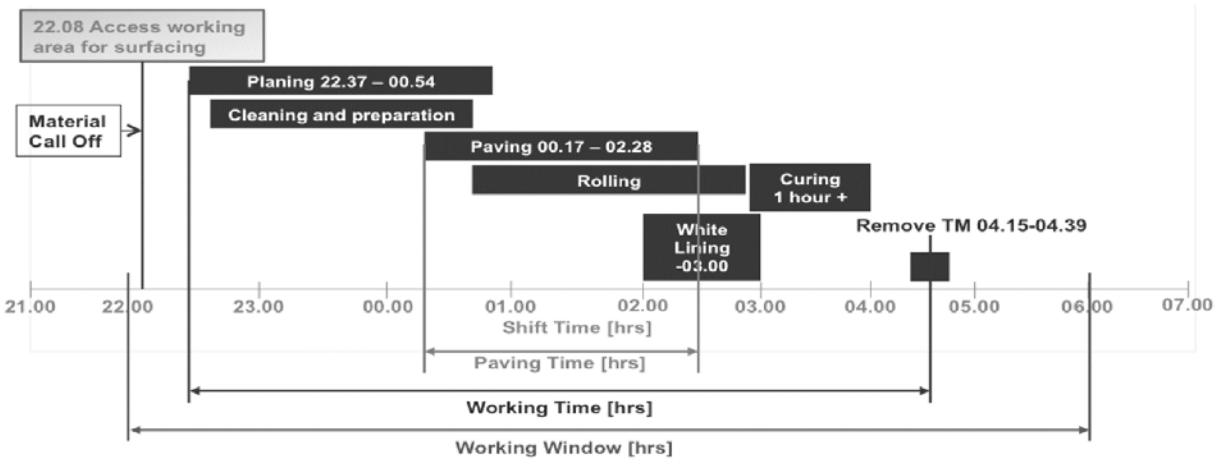


Figure 4.3 Road Resurfacing Operation, 'As-is Process', Moore, A. (2015).

4.3.2 After improvement with Lean

After the improvement, the team mapped the new stage or the improved stage which is shown in Figure 4.4 below. It can be seen that the paving time has mostly increased from 2 hours 11 minutes to 6 hours and 50 minutes. The paving operation is the most critical key performance indicator in the whole process, and any improvement here will directly uplift the total efficiency.

Figure 4.4 displays that the planing started at 21:45 rather than 22:30 and continued till 3:00 rather than 1:00 in the as-is stage.

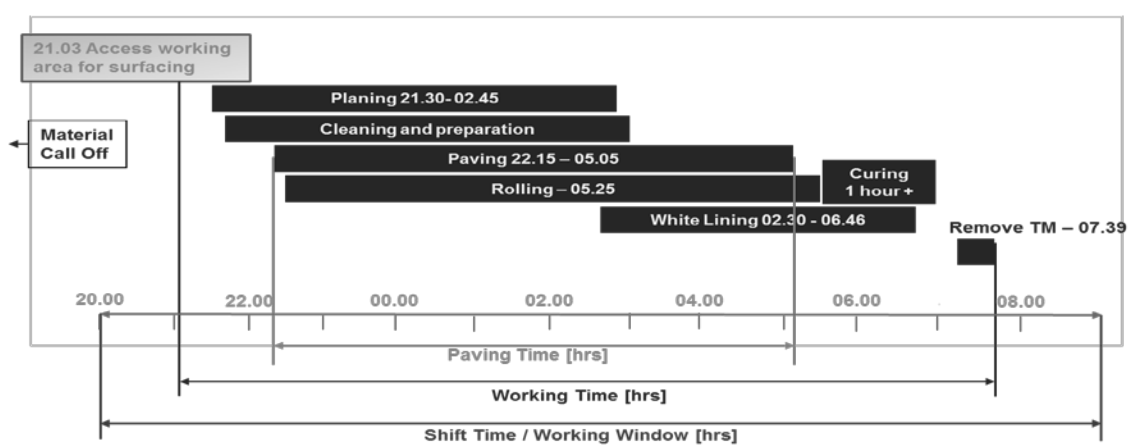


Figure 4.4 Road Resurfacing Operation, Improved Process, Moore, A. (2015).

By analysing the before and after improvement stages of the resurfacing process, many interesting findings were made. Massive improvements were identified in the improved phase, and some of them are shown in Table 4-1 below.

Table 4-1 Improvement Comparison before and after Lean.

Activities	Baseline Process	Improved Process
Shift Duration	10 hours	10 hours (staggered)
Working Window (Theoretical)	8 hours (22:00 – 06:00)	13 hours (20:00 to 9:00 am)
Paving Duration	2 Hr 11 Min	6 hour 50 minutes (22:15 – 5:05am)
Tonnage Laid	298 Tonnes	1024 Tonnes
Paver Productivity (i.e. Pavement Time/Full Working Time)	33 % (2Hr 11 Min / 6Hr/ 31 Min)	64 % (6hr 50 min / 10 hours 36 mins)
Average hourly tonnage laid	137 T (at 45 mm thin surfacing)	149 T (at 45mm thin surfacing)
Pavement length laid (in meters)	938 m	2700 metres

4.4 Systemization and Testing Stage

After collecting the relevant data, it was essential to define the boundaries of a simulation study. The scope of simulation development in this study is limited to all activities involved from road surfacing activity start (i.e. from the time of road closure for surfacing purpose) till the road is back in operation. The restraints in material deliveries, programming of the project, or what goes on at asphalt plant/quarry level are beyond the scope of the presented simulation. After defining the boundaries, it is essential to identify the assumptions that were made to study the system in a stress-free way and to set the external environment.

Preparation and logistic activities were included in the model, taken as fixed timings as measured on-site, and are not part of the analysis. The simulated operation activities included planing, sweeping and pitch spraying, paving, rolling, white-lining, and testing. Any sub-activities within each one of these activities is not considered. All required material in the process is assumed to be always available and delivered on time (Aziz, Qasim and Wajdi, 2017). Downtime of equipment is not included in the simulation. The Simulation is based on paving 45mm thick surface course and the software used to simulate the process is called Simio. The process was divided into several steps to achieve the desired goals.

The primary purpose of Discrete Event Simulation is to experiment with various options that are otherwise not possible in real life situations. Some of them might be very expensive to trial where others are just not possible; however, they can be trialled in a computer environment which is safe, cost and time efficient and environment-friendly. Figure 4.5 below shows the 3D view of the simulation model developed for this resurfacing case study.

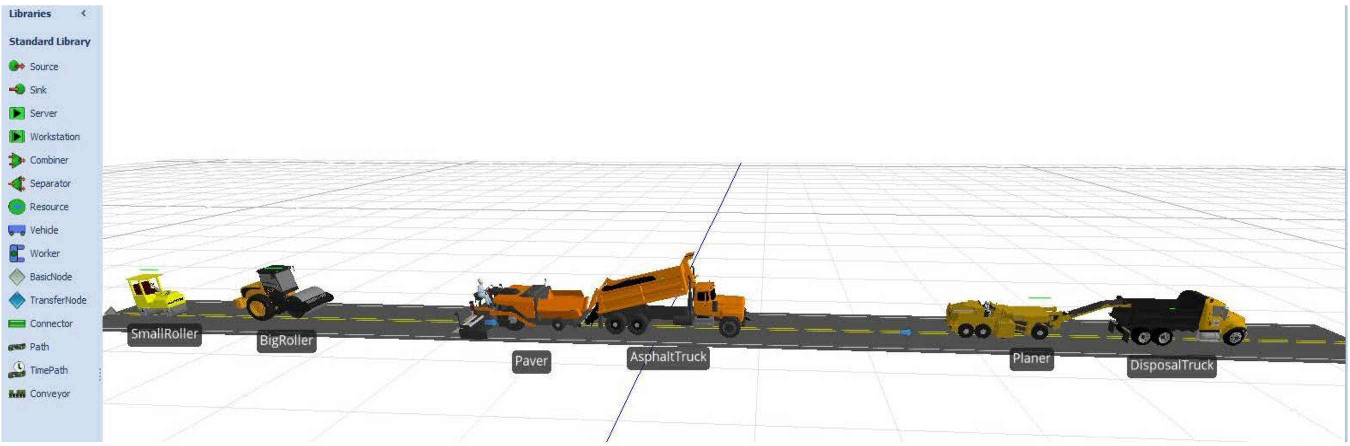


Figure 4.5 A 3D view of the Simulation model created for 1000 tonne case study using Simio.

4.4.1 Scenario No.1: Creating Zones within the job site.

The first scenario assumes dividing the job site into two equal zones, Zone A & B, as illustrated in Figure 4.6 below. Each zone has its own planer; a paver and both zones share five sweepers and 4 rollers. During this, two lanes are closed for resurfacing and two lanes open to public traffic maintaining the same working window. The key expected outcome is increased production inlaid asphalt. The cost may rise for additional machinery arrangements, but if it improves the overall productivity, it means that more length of road will be paved and it will be beneficial for the client.

Figure 4.6 Simulation scenario 1

Simulation output is illustrated in Table 4-2, with total production rate increased up to two times (i.e. 276.9 Tonne/hour) the standard production rate. The simulation shows that the utilisation of pavers through the working window remains the same, despite added machinery with an average usage rate of 65.3%. As a result, an increment in the values of total production and production rate was expected, and the outcomes of simulation met these expectations. Even though production output has increased, the added cost because of additional machines should also be taken into account (Aziz, Qasim and Wajdi, 2017; Qasim and Aziz, 2017b).

Table 4-2 Results of Scenario1.

Scenario 1: Using Two pavers and working in zones behind each other			
Paver total output	Paver Avg. output	Paver 1 utilization	Paver 2 utilization
1892 Tons	276.9 Tons/hour	65.3%	65.3%

The upside of this scenario is that the total paver output is increased and the total amount of laid asphalt is almost doubled, however, it comes at the cost of extra machinery used in this scenario. This can also be justified as paving is the most critical KPI in resurfacing and contractors are penalised or rewarded based on the amount of asphalt they have laid in one shift (night). If the projects are running late, contractors can use this technique to double the length of the paved road and the overall output. It will not only increase the total production but will also impact the working style and reduce waste, if the lean manufacturing approaches are used every day.

Another significant advantage of using two pavers behind each other is that no extra Traffic Management is required for the additional machine. The asphalt lorries and waste dump trucks will keep using the additional lane that is usually shut next to the working lane. In various countries, the contractors are rewarded for early completion of such projects. If the reward amount is much higher than the additional cost of the extra paver, which it should be, it is an ideal scenario to use multiple pavers.

Variables in this Simulation Scenario: 1							
Number of Pavers	Number of Planers	Number of Rollers	Number of Sweepers	Number of Lanes being paved	Number of Breaks in the shift	Site divided into zones?	Shift duration
2	2	4	5	2	1 long break	Yes, 2 zones	10 hours

Table 4-3 showing list of variables used in Scenario 1

4.4.2 Scenario No.2: Taking two small breaks rather than one 30-min long break

This scene focuses on measuring the impact on production rates of a 30-minute worker break from 2:00 am to 2:30 am. Single paver operations are assumed. A traditional 30-minute break resulted in a decrease in total production and production rate. A 30-minute break leads to asphalt laid reducing to 865 Tonnes in comparison with the previous scenario of 1892 Tonnes output. The primary reason is the switching off of machinery. Planer vehicle has a large drum blade attached on its front to shave the top surface off the road. This machine takes a long time to warm-up, and if it is turned off during the break time, it will again waste time as it did before the resurfacing commenced.

As a result, staggered break times are suggested, in which each team takes its break in a manner that does not affect the flow of work, and the machines are kept running smoothly. The key expected outcome is increased output, i.e. non-stop paving operation throughout the working window. However, it is usually a challenge to modify the current working style of people and to get the extra workforce to keep the process running.

The production rate was recorded as 126.6 Tonne per hour, respectively. The utilisation of Paver through the working window shrank by 5.6% which is not suitable for the process, and short breaks are suggested during the operation. In this case, the resurfacing procedure will not stop for a long time, and the machines will not require warm-up time again. Table 4-3 Results of Scenario2 shows the results of scenario 2 with increased paver utilisation compared to standard scenarios.

Table 4-4 Results of Scenario2.

Scenario: 2 Taking two small breaks rather than one long break		
Paver total output	Paver Avg. output	Paver utilization
865 Tons	126.6 Tons/hour	59.7 %

Table 4-5 below shows number and data of variables that were used in this scenario.

Table 4-5 showing list of variables shown in Scenario 2

Variables in this Simulation Scenario: 2							
Number of Pavers	Number of Planers	Number of Rollers	Number of Sweepers	Number of Lanes being paved	Number of Breaks in the shift	Site divided into zones?	Shift duration
1	1	2	2	1	2 small breaks	No, 1 zone	10 hours

4.4.3 Scenario No.3: Shutting and paving two lanes at once.

The third Scenario assumes limiting motorway closures to a 6 km stretch. Three lanes at a time are closed to public traffic (where possible e.g. on Motorways), and one is left open, and 45mm thick asphalt is to be overlaid. Each closure interval (2 lanes) requires one extra hour to complete resurfacing of the closed lanes. The additional hour is needed for the paving operation. This scenario will almost double the amount of asphalt laid and will resurface two lanes at once, however, shutting about three lanes at once might not be possible in many cases. Table 4-4 below presents the results of scenario 3, and it can be seen that the paver utilisation is improved to a considerable extent as compared to as-is and scenario 1. Both the pavers are working at 65.3% efficiency, and the amount of asphalt is laid as double quantity. Since two lanes are paved at once, and it will save another night's work, the use of additional machinery can be justified here.

It can be possible on motorways where there are more than 4 running lanes, and 3 of them can be shut using traffic management. One of the lanes would be used for accessibility of dump trucks and asphalt deliveries, and the other two can be paved simultaneously using two pavers and planers. This will be an expensive option; however, as discussed in scenario 1, it can be practised to finish the work earlier and will result in fewer disturbances for the road users.

Table 4-6 showing list of variables used in Scenario 3

Variables in this Simulation Scenario: 3							
Number of Pavers	Number of Planers	Number of Rollers	Number of Sweepers	Number of Lanes being paved	Number of Breaks in the shift	Site divided into zones?	Shift duration
2	2	4	5	2	1 long break	No, 1 zone	10 hours

Table 4-7 Results of scenario 3.

Scenario 3: Closing two lanes at once			
Paver total output	Paver Avg. output	Paver 1 utilization	Paver 2 utilization
1892 Tons	276.9 Tons/hour	65.3 %	65.3 %

4.4.4 Scenario No. 4 closing the road for 55 hours like California.

In California, the road is usually closed for maintenance on weekends for 55 hours starting from Friday night on Monday early morning. There are more room and freedom for paving machines to work, and they do not need to be transported every day which wastes time and resources. The difference in outputs and paver efficacy can be seen in Table 4-5 below. It will save time and cost for TM and transport machinery and will increase the output. However, it will require early planning to shut a road entirely and will not be possible at various locations at all.

The results are auspicious in this scenario, and Table 4-5 displays that the average paver put is 358.4 tons/hour which was only 126 tons/hour is normal circumstances in the UK. It happens because the machinery keeps operational for most of the time without disruption and warm up periods etc. The paver utilisation is also at the highest peak, i.e. 71%, and no other scenario showed such productive results. The most improved factor is the total amount of asphalt laid. If we measure the amount of asphalt laid each night in the UK, it comes up to roughly 865 tons each night and if that is multiplied by 3, it becomes 2595 tons. However, the amount of asphalt laid in California during these three days is more than 15,000 tons. It is because of the non-stop work, reduced wastage and non-value adding activities that are common here.

This scenario is the most efficient as the machines work up to their maximum capacity and no time is wasted while putting and removing Traffic Management (TM) protocols. If the road is shut for 55 hours, it is equivalent to 7 regular shifts in the UK of 8 hours each. It implies that traffic management would have been used seven times which is only required once in this scenarios. It will not only save time during pacing but will directly save resources spent on TM. The biggest challenge is the nature of roads in California is different to the UK. Not all the streets can be shut for the whole weekend due to disruption caused by it, and if there are no alternative routes etc., it is impossible. Lastly, local governing bodies also have different rules and protocols regarding road closures and this scenario may not be applicable on a vast scale.

Table 4-8 Results of scenario 4.

Scenario 3: Closing two lanes at once			
Paver total output	Paver Avg. output	Paver 1 utilization	Paver 2 utilization
15,954 Tons	358.8 Tons/hour	71 %	71%

Table 4-9 showing list of variables used in Scenario 4

Variables in this Simulation Scenario: 4							
Number of Pavers	Number of Planers	Number of Rollers	Number of Sweepers	Number of Lanes being paved	Number of Breaks in the shift	Site divided into zones?	Shift duration
2	2	4	5	2	Staggered breaks	No, 1 big zone	55 hours

4.5 Documentation and Guidelines

4.5.1 Modelling of Current State

In this case study, the fundamental aim was to understand the current state of a paving operation on the ground level and its performance in various what-if scenarios. The best and most optimized scenario was also identified at the end. Software called Simio was chosen for this analysis because of its powerful animation and experimental capabilities.

a. Number of vehicles and functions

The current state of a typical system has a total of 9 vehicles involved in the resurfacing process. The process starts with the Traffic management vehicle which is used to place the safety cones on the road. Once the work starts, planing machine starts shaving the top layer of the road and dumps the shavings and old tarmac in a dump truck. The description of vehicles is:

i. Vehicle 1: Traffic Management Vehicle to place cones on the road.
ii. Vehicle 2: Planer or Milling vehicle to remove the top/old surface of the road.
iii. Vehicle 3: Dump trucks to transport the waste (scraped off asphalt) to the quarry for recycling.
iv. Vehicle 4: Sweeper to clean the road from any debris before paving starts.
v. Vehicle 5: Paving vehicle to lay asphalt on the roads, bridges, parking lots etc.
vi. Vehicle 6: Asphalt loaded trucks to bring asphalt from quarry to the desired road.
vii. Vehicle 7: Roller 1, Drum roller to compress the asphalt and make the surface even.
viii. Vehicle 8: Roller 2, Tire roller to give a smooth finish.
ix. Vehicle 9: White liner vehicle to draw white or yellow lines on the road.

b. Model entity and source

The model entity, in this case, is Asphalt since it is first taken off the existing road and then new tarmac is placed back using pavers. Therefore, the model entry is named “asphalt” which was used to calculate truckloads. To make the 3D simulation more realistic, a symbol is applied to this entity that is black coloured and cubic shape to represent a piece of tarmac. If it is defined in the beginning, it would be easier to calculate the total weight of asphalt removed and laid back at the end of the process. A source was created for vehicles and a second source was created to “Generate Asphalt” for the simulation. Source 2 is linked with the Milling machine, as soon as the milling machine starts working on the road, “GenerateAsphalt” process will start at output@Ashphalt source. Triggering event for generating new entities is chosen as output@Ashphalt so that each time an entity “piece of asphalt” exits the excavator, a new “piece of asphalt” will be created. Therefore the system will never run out of the material source, and there will be no excess entities in the system that will slow the simulation. “Generate Asphalt” source item is connected to Miller by a connector so that each new entity created will be present at the dump truck (in front of planer vehicle) in no time.

c. Trucks, nodes and paths

In the initial state of the system there are total 9 vehicles, however, if a full simulation model is generated, it will have to keep in account the changing dump trucks. To maintain the simplicity of the model, an initial number in system value is set to 4 under population properties of Vehicle3, (dump trucks). The actual number of required dump trucks will depend on the type of job and the length of the road to be paved or milled; however, it can be altered in the simulation model depending on the situation. The initial speeds of vehicles are different, based on the average travel on the road; however, their working speed differs during the actual paving operation. Again, this is dependent on the type of road, its layout, weather, work conditions etc. but it can be modified by clicking on a vehicle and selecting its properties as shown in Figure 4.7 below:

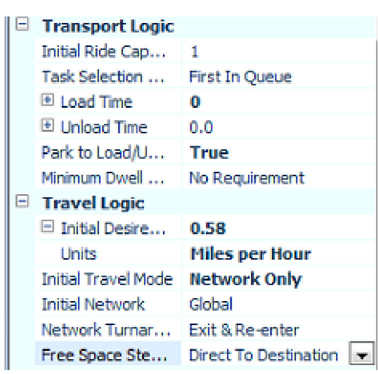


Figure 4.7 Travel properties of vehicles in Simio.

d. Status Label Animations

In order to follow the utilization rates and other KPI's such as average waiting times and total travelled distance of trucks during the simulation run, it is required to add status label animations in the model window.

- The utilization rate of the paver and planer is calculated by following formula; "Paver.ResourceState.percent.time" and "Planer.ResourceState.percent.time".
- Average waiting time at asphalt trucks Is calculated by following formula; "DumpTrucks.Output.ParkingStation.Contents.AverageTimeWaiting"

Experimentation

In order to do experiments in Simio, first, control parameters have to be defined. In this particular case, the parameters are defined as a number of vehicles involved, the speed of machines and their processing times. In order to add these inputs as control parameters, developers right clicked on the name of each of these inputs and chosen Set Referenced Property, and then Create New Referenced Property option from the list. Each of the Referenced Properties was named corresponding to the name of the input, such as "Planer.ProcessingTime" for the processing time of the Planer vehicle and "Paver.ProcessingTime" for processing time of Paver and so on.

Once all the control parameters were defined, a new experiment was created. In the experiments window one can see the control parameters defined before, but the responses of the system have to be established as well which corresponds to the KPI's of our model, so that once someone changes the value of a control parameters, they will see the change in the value of KPI's such as utilization and total distance of trucks. This will help in understanding the outcome of various what-if scenarios according to the given inputs.

In order to see the value of KPI's for each scenario, one needs to assign them as responses in the experiments window. In order to do that, they can click on Add Response button. First, they can directly input the name of the response, and in the expression field, they can copy the function created for animation of this KPI in the model window. For instance, the author named the response PaverUtilization and entered “Paver.ResourceState.percent time” formula for the utilization rate of the Paver.

The general process of experimentation is explained in more details with step-by-step instruction and pictures in section 5.5.1.

4.6 Validation and Refinement Stage

The technical validation of the model was performed using the initial data captured for the experimentation. After that it was also tested using artificial (made up) data that could predict the outcomes easily and explain if the model is working properly. The validation of this artefact (simulation model and its guidelines) was performed in two stages:

1) Validation through the theoretical artefact evaluation process
2) Validation from a focus group of experts.

4.6.1 Validation through the theoretical artefact evaluation process

Firstly, the artefact (simulation model and recommendations based on it) was validated using the hybrid method designed by Prat et al. (2014) which is also shown in Figure 4.8 below. This method is based on a theoretical checklist that acts as a rigorous testing method for newly developed solutions or artefacts. In order to respond to this, the answer is divided into 5 significant dimensions as shown in Figure 4.8 below. The central system dimensions it includes are the goal, environment, structure, activity and the evolution of the artefact. Each aspect is then further divided into criteria and sub-criteria for an apparent breakdown of an artefact into visible parts. The dimensions are comprehensive regarding evaluation criteria and further sub-criteria to ensure the developed artefact is functional, precise and useful.

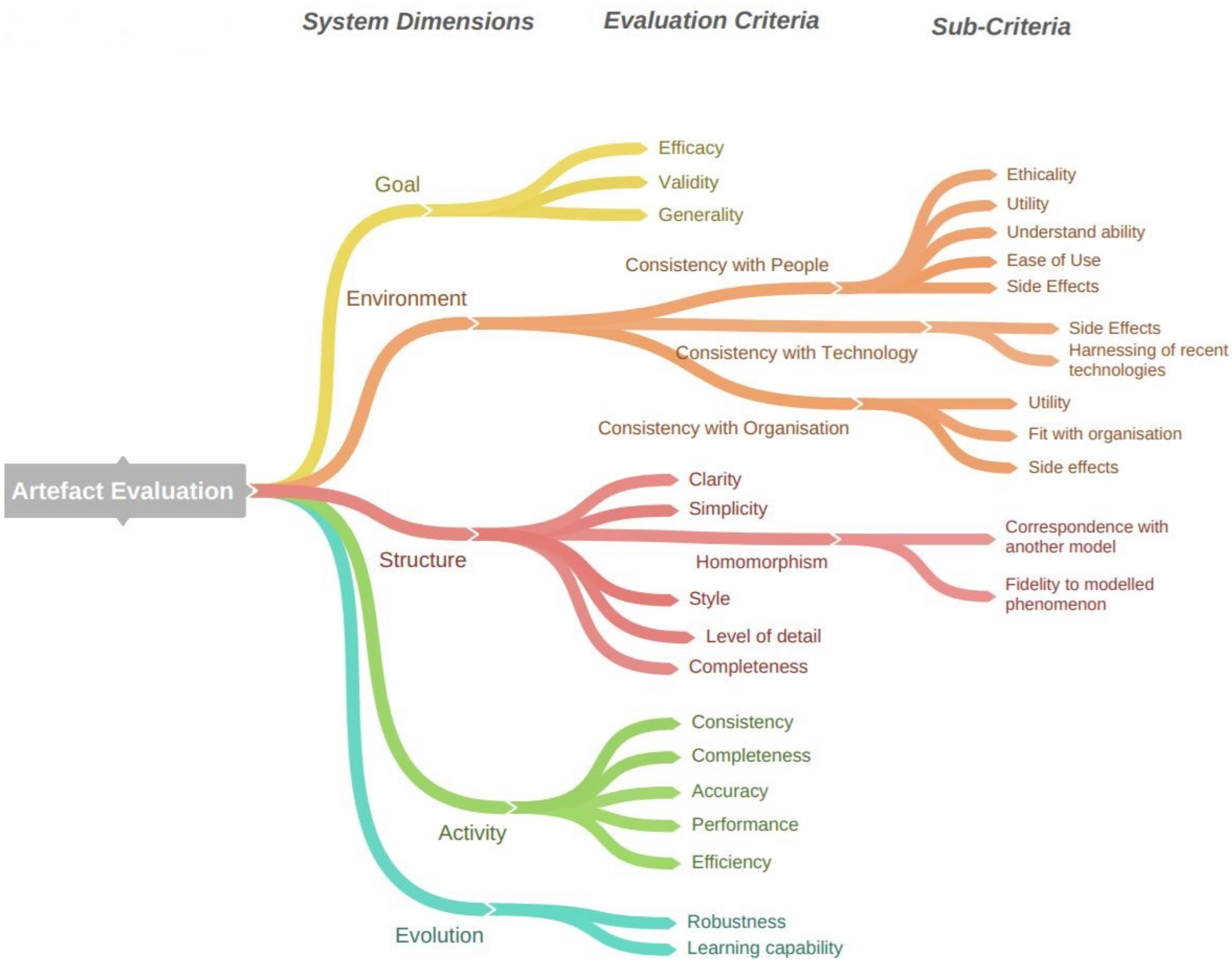


Figure 4.8 Hierarchy of Criteria for Artefact Evaluation, Prat et al. (2014).

4.6.1.1 Goal

The end goal was to enhance the as-is process of resurfacing operation which was performed through the integration of lean and simulation methods. The developed Artefact (simulation model and its recommendations) is efficient because it fulfilled the initial aim of this case study, i.e. to reduce waste and improve the operation. It ensured the maximum utilisation of the resources and the working window and reduces wastages in the form of unnecessary delays and breaks. Tens of runs have confirmed its validity in the computer-based environment and during the workshop by experts. The developed model ticks the generality box as well due to its applicability in all resurfacing scenarios, different road layouts, different machinery used, changeable weather constraints, varying traffic on the road etc. It can be applied to almost any country in the world as well since the method and machinery for resurfacing is similar. Figure 4.9 shows the properties tab on the left side where transport logic, riding capacity, loading and unloading time, parking conditions, travel speed and mode can be defined. It shows the level of detail of information which goes into a functional simulation model. These properties have to be determined for each and every resource in the environment. In the centre, the model is shown just before the vehicles step on the road. The cones can be placed according to the need by simply selecting them all together and moving them using a mouse. On the right side, “source” is selected and its properties are displayed. The source is responsible for creating traffic vehicles on the road which can be controlled according to the needs of a scenario.

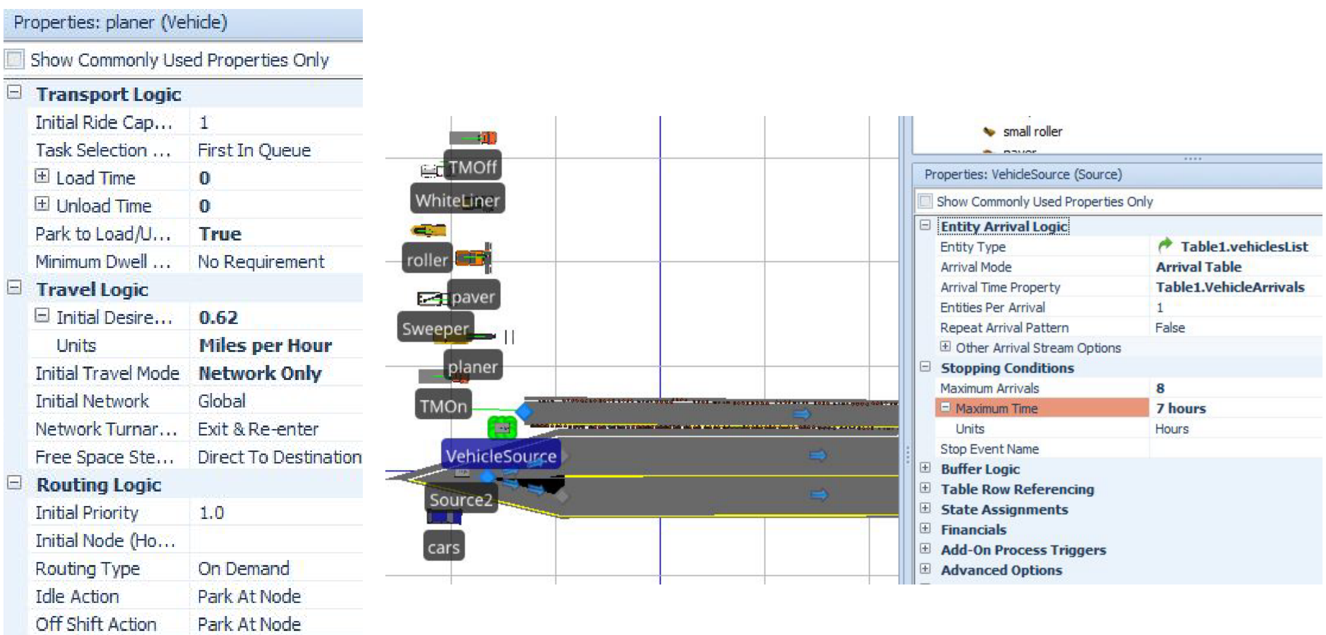


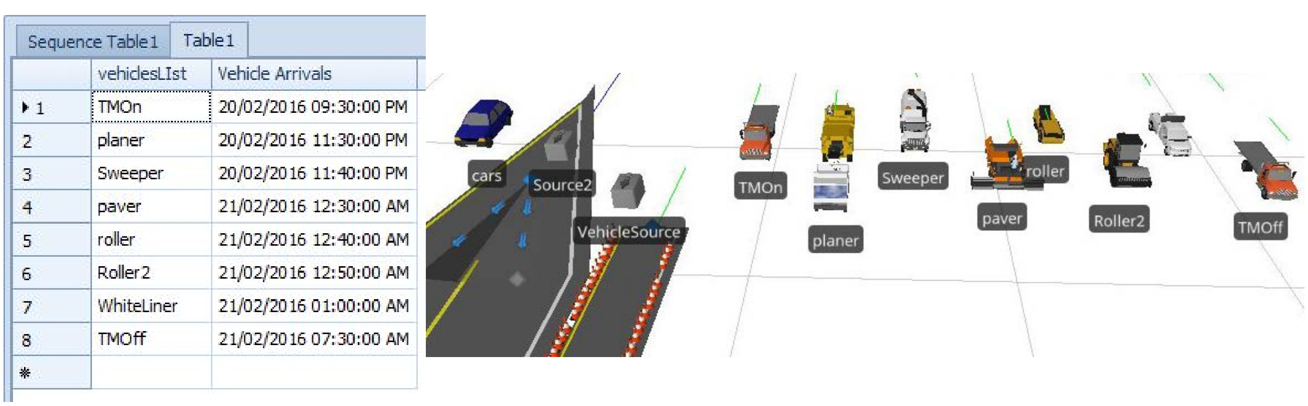
Figure 4.9 Modifiable transport and travel logics that can be adjusted according to needs of different cases/countries. Screenshot of Simio model.

4.6.1.2 Environment

The environment in this aspect means business environment where organisation, people involved and the machinery being used (Hevner et al. 2004). The developed artefact should establish its consistency with these three viewpoints. Regarding consistency with the organisations, the utility of the developed simulation model responds thoroughly. Majority of construction firms responsible for resurfacing are perpetually keen to advance their construction processes to maximise resources utilisation and hence profit. They can adopt the simulation model to identify waste and diminish it as much as practically possible. This simulation model is very relevant concerning the compatibility with people due to its simplicity and understandability.

Its development and operation have been illustrated in detail which will assist people using the combination. It is also harmonious with the recent technologies used by the majority of organisations as most of the construction-related software packages have built-in simulation modules as well. Companies can use the model created in this case study without the need to buy any particular software which will further save capital. Since there is no mention of a specific organisation or their data etc., so there are no ethicality concerns, and it can be replicated without hesitation. The only downside it has is that the person running this software needs to have some fundamental knowledge about simulation techniques and how they work, which is not complicated and there are various free resources on the internet to obtain it.

Figure 4.10 below demonstrates the sequence of vehicles and their detailed schedules which will decide the arrival of vehicles on the road, the time that they will take to travel and how many times will they be loaded and unloaded. It also shows the sequence of the overall operation like the process starts with traffic management and then planing and resurfacing and so on and finishes with traffic management vehicle as well.



	vehiclesLIst	Vehicle Arrivals
1	TMOn	20/02/2016 09:30:00 PM
2	planer	20/02/2016 11:30:00 PM
3	Sweeper	20/02/2016 11:40:00 PM
4	paver	21/02/2016 12:30:00 AM
5	roller	21/02/2016 12:40:00 AM
6	Roller2	21/02/2016 12:50:00 AM
7	WhiteLiner	21/02/2016 01:00:00 AM
8	TMOff	21/02/2016 07:30:00 AM
*		

Figure 4.10 Resurfacing Vehicle's schedule that has ability to adapt from different sub-contractors.

4.6.1.3 Structure

Structure of an artefact can be assessed by its simplicity, style, level of detail, completeness, consistency and homomorphism. The artefact, the simulation model and its guidelines are pretty simple regarding its development and practice. Difficult technical expressions are avoided as much as possible to enhance its simplicity and thus the applicability. A person with basic knowledge of IT and simulation can follow the procedures outlined in section 4.4 and achieve their desired goals. The method of development and the model is quite generic and is widely used globally. The software used for its formulation is readily available for free as well as paid options for businesses exist. However, a free (demo) version can also run the developed model due to its advanced yet straightforward style. While the artefact is understandable and straightforward, however, its level of specification is exceptionally high. The data required for the creation of such a model may take months to gather and then further time is needed for its development, rigorous testing and refinement.

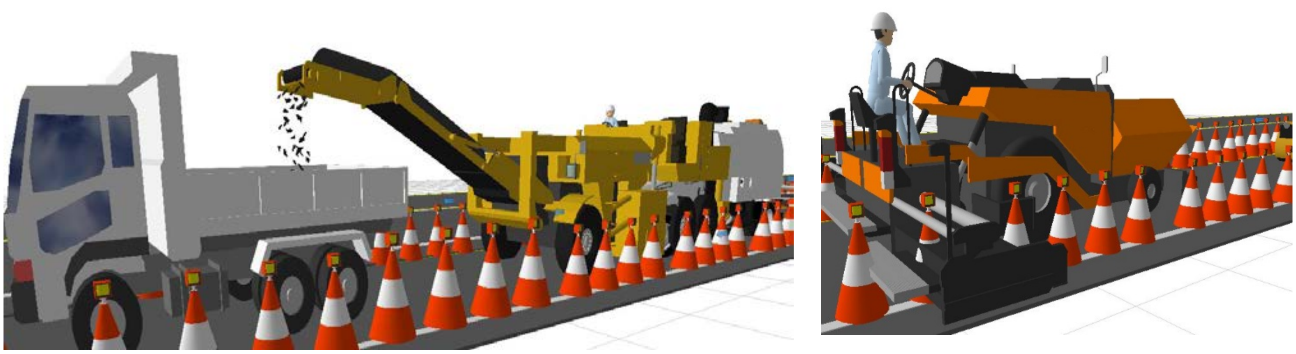


Figure 4.11 Powerful 3D visualisation abilities of Discrete Event Simulation modelling.

Discrete Event Simulation as described in section 2.3 in detail requires the highest level of data/specifications/information to work accurately compared to the other two modes of simulation, i.e. agent-based and system dynamics. The model along with its comprehensive description and guidelines makes it complete and consonant. A complete artefact explains in detail about how and why it was produced, its validation and instructions/guidelines for practice. Lastly, homomorphism means its correspondence with other models and fidelity to modelled phenomena. Figure 4.11 above shows the 3D visualisation from the simulation model which can be rotated from all sides and angles. It is also very helpful in understanding the process by making the best of use of this rotating feature.

The simulation model developed in this case study corresponds adequately with other simulation models, e.g. currently, it only deals with the operation stage of resurfacing vehicles working alongside roads; however, it can also be associated to other models concerning the delivery of materials and possible delays as well as risk reduction models. Regarding fidelity to the modelled phenomenon, this model has impressive 3D graphics which mimics the original process very well making it easy to understand for technical as well as non-technical people. The level of detail used and the focus groups with experts evaluated its exactness and precision.

Figure 4.12 below shows the interface of resurfacing simulation model developed in Simio. On the top ribbon, it displays all the time-related parameters like a number of runs start and ends time and date and the speed of runs. Left panel shows drag and drop library where the standard items are placed and can be used for any model. They include vehicles, operators, machines, servers, nodes and paths etc. The background is originally white for better display. However, it can be changed with colours, pictures or the actual maps as done in the next case study.

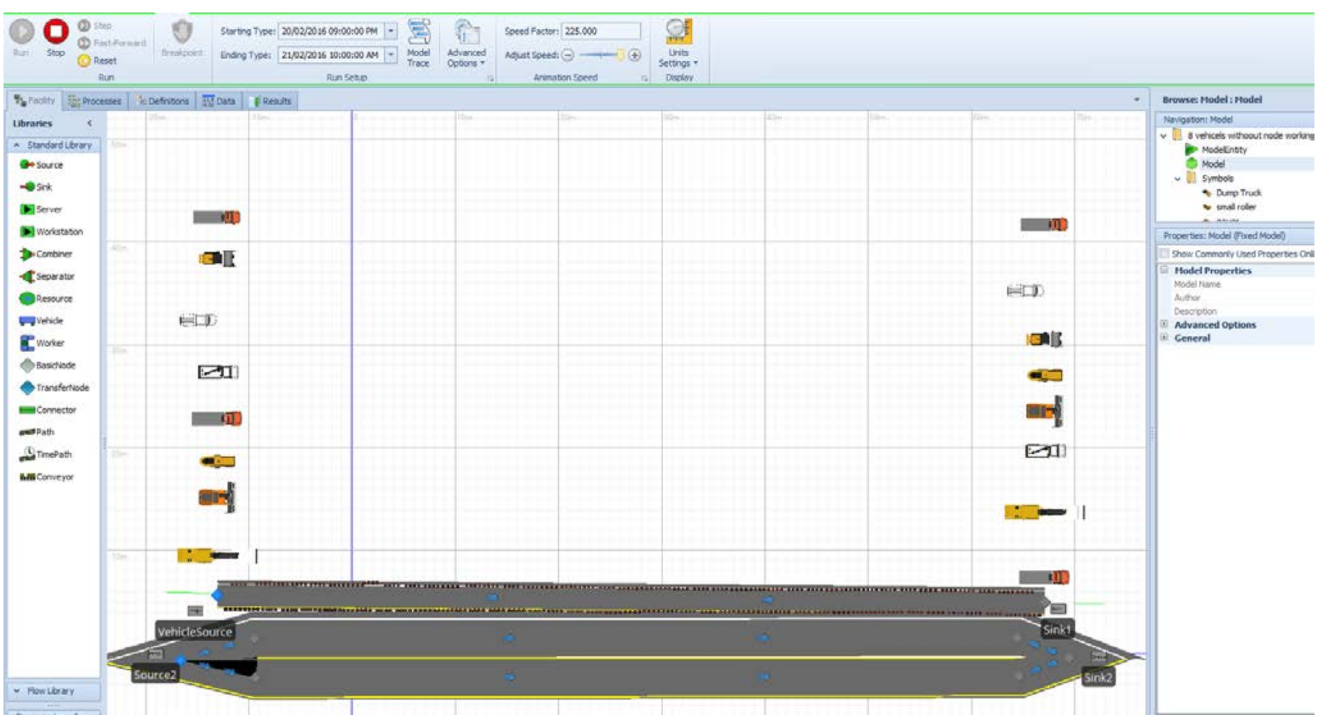


Figure 4.12 Interface of Simio which shows many features on left, right and top screen.

4.6.1.4 Activity

Activity dimension is characterised by the accuracy, performance, efficiency, completeness and consistency of a developed artefact. The developed artefact is accurate, exact and precise due to its maximum level of detail. Its performance has been experimented and validated theoretically as well as with experts in simulation and construction processes in the United Kingdom. During the focus group workshop, the model was explained and demonstrated in detail, and the experts also ran various experiments to examine its performance and capableness. Its efficiency is also evident from the fact that it does not require some specific machines to run or specialised knowledge about simulation yet works well to improve any as-is resurfacing process regardless of the structure of road, traffic or other varying conditions.

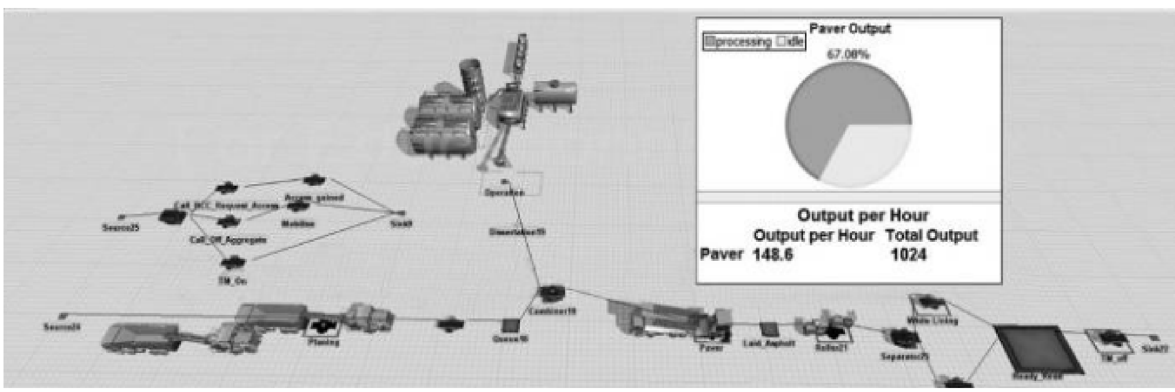


Figure 4.13 Paver's output per hour in one of the tested scenarios along with the 3D layout of the whole process, Aziz, Qasim and Wajdi, (2017).

The consistency and completeness can be assessed from its ability to work with other models, adapt to changes promptly, functionality remains similar in any scenario etc. All these factors have been applied to the developed simulation model and its guidelines, and it has passed all the tests. Figure 4.13 above shows the output of a paving vehicle in FlexSim software for the same case study. Different result ribbons in all these software can be produced and attached on the main screen for enhanced understanding of outputs while modifying variables like speed, the distance between them, and a number of resources etc. It also shows the idle time for each resource during the experimentation.

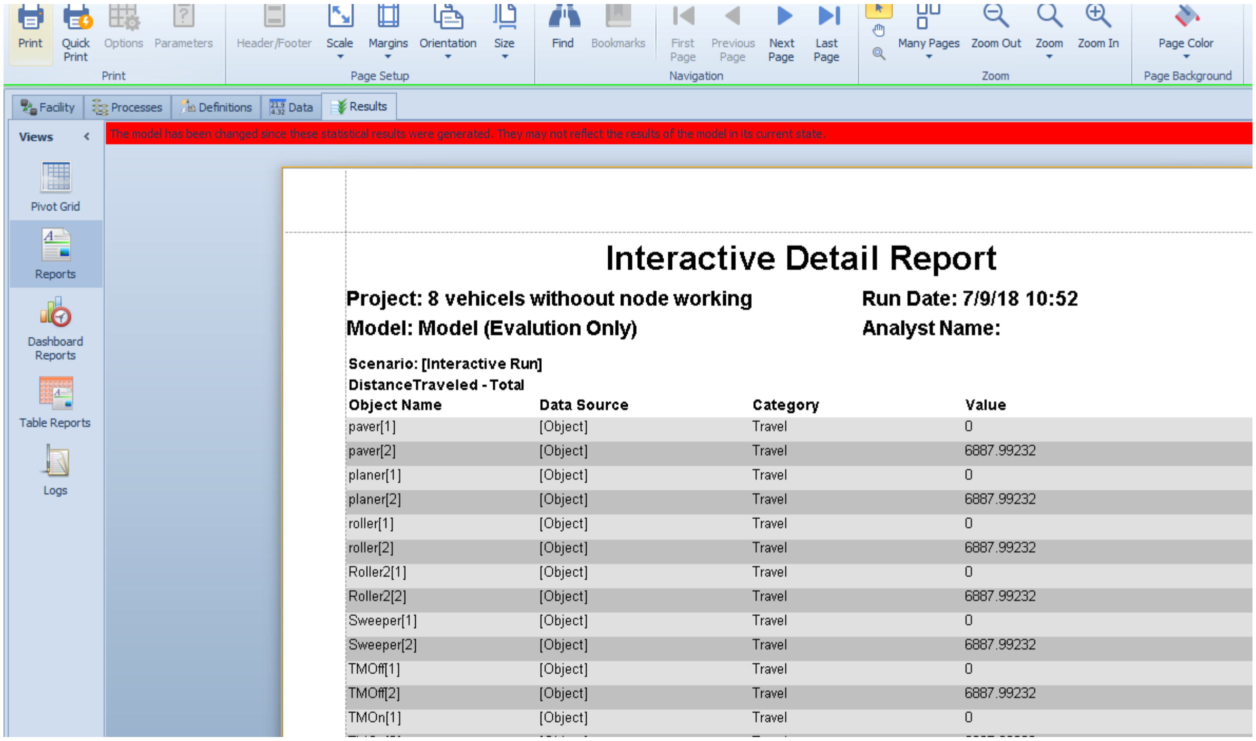


Figure 4.14 Interface of Simio software to collect results as reports, pivot grid, table reports and logs.

The results feature of Simio is pretty strong. Once a shift has stopped running, or the experiments have been performed, it will automatically generate the results using pivot grids, reports, charts, tables and logs of operations.

Figure 4.14 above shows the interactive report created by Simio which can be altered according to the needs for reporting. By default, it will include all the features like utilisations, idle time, breakdown periods, bottle-necks and break of all the resources. However, these features can be turned on or off by just selecting them and clicking the on/off button.

Similarly, in the pivot table, results can be dragged and dropped to place next to each other for better understanding and to match various resources against each other. Figure 4.15 on the next page shows the results automatically generated after the experiments in this format. “Pieceofearth” entity was used to measure the amount of tarmac which has been laid on the road as it is the key performance indicator in the resurfacing process. Similarly, idle times of large vehicles can give an indication about the mistakes in the scheduling and execution of the process.

Design | Response Results | Pivot Grid | Reports | Input Analysis

rop Filter Fields Here

Average | Minimum | Maximum | Half Width

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Scenario1 Average	Minimum	Maximum	Half Width
odelEntity	PieceofEarth	[Population]	Content	NumberInSystem	Average	266.1997	64.2838	267.5802	0.8112
					Maximum	528.8000	25.0000	533.0000	1.6792
			FlowTime	TimeInSystem	Average (Ho...	11.8464	11.8237	11.8667	0.0103
					Maximum (Ho...	23.4592	23.3220	23.5336	0.0482
					Minimum (Ho...	0.2491	0.2405	0.2603	0.0047
					Observations	261.3000	59.0000	263.0000	0.8294
			Throughput	NumberCreated	Total	789.8000	84.0000	796.0000	2.4962
				NumberDestroyed	Total	261.3000	59.0000	263.0000	0.8294
ink	Sink2	[DestroyedEntities]	FlowTime	TimeInSystem	Average (Ho...	11.8464	11.8237	11.8667	0.0103
					Maximum (Ho...	23.4592	23.3220	23.5336	0.0482
					Minimum (Ho...	0.2491	0.2405	0.2603	0.0047
					Observations	261.3000	59.0000	263.0000	0.8294
		InputBuffer	Throughput	NumberEntered	Total	261.3000	59.0000	263.0000	0.8294
				NumberExited	Total	261.3000	59.0000	263.0000	0.8294
ource	GenereteEarth	OutputBuffer	Throughput	NumberEntered	Total	789.8000	84.0000	796.0000	2.4962
				NumberExited	Total	789.8000	84.0000	796.0000	2.4962
		Processing	Throughput	NumberEntered	Total	789.8000	84.0000	796.0000	2.4962
				NumberExited	Total	789.8000	84.0000	796.0000	2.4962
ehicle	Vehicle1	[Population]	Capacity	ScheduledUtilization	Percent	40.1331	39.9902	40.2551	0.0543
				UnitsAllocated	Total	525.0000	21.0000	529.0000	1.6519
				UnitsScheduled	Average	4.0000	4.0000	4.0000	0.0000
					Maximum	4.0000	4.0000	4.0000	0.0000
				UnitsUtilized	Average	1.6053	1.5996	1.6102	0.0022
					Maximum	2.0000	2.0000	2.0000	0.0000

Figure 4.15 Results displaying ability of Simio software which can easily be adjusted according to needs.

4.6.1.5 Evolution

Evolution is the robustness and learning capability of an artefact. As mentioned in above points, resurfacing simulation model was tested under various changing conditions by the developer and the assessors, and it demonstrated success in withstanding adverse conditions and harsh testing.

Figure 4.16 below shows the floor plan of the same process and case study which was also modelled in the FlexSim software. It assists in understanding the overall process by visualising in just one screen with all the relationships between the resources and sources as shown below.

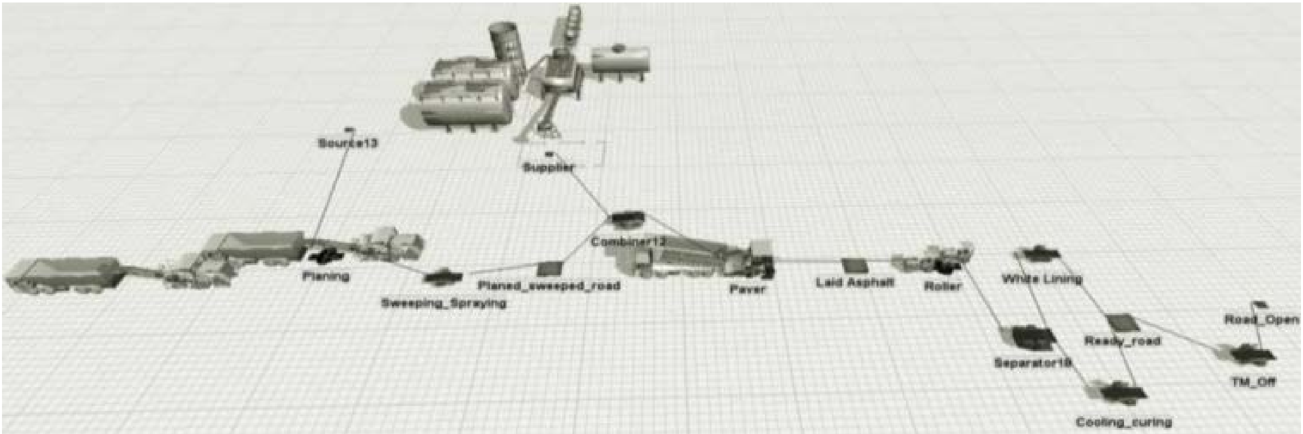


Figure 4.16 Simulation of floor plan in FlexSim, Aziz, Qasim and Wajdi, (2017)

The learning capability of this artefact is very vast because this developed model only deals with operation stage of resurfacing; however, it can be populated with more details or can be linked to other models regarding materials delivery, risk assessments, effects of severe weather, decision process modelling, resource management and other information can be added as well. Figure 4.17 on the next page shows the elements tab of a simulation model which is a prominent feature in almost all the simulation software packages. Here, users can define and modify the properties of all the resources and attach different events and tokens to them. An event, in this case, can be the breakdown of a vehicle which will ultimately affect the overall process. This event can be defined in the events tab, and it will ask for a condition when it can be triggered and what will happen once it is triggered. Once it is set, it will save the settings and act accordingly if it occurs in the future.

Entities are object models that can be dynamically created and destroyed, have a real location within the facility window and their movement into and out of objects may trigger an event. Tokens are generated inside the process and are destroyed at the end of the process. It can be stated that processes and their steps are executed by tokens.

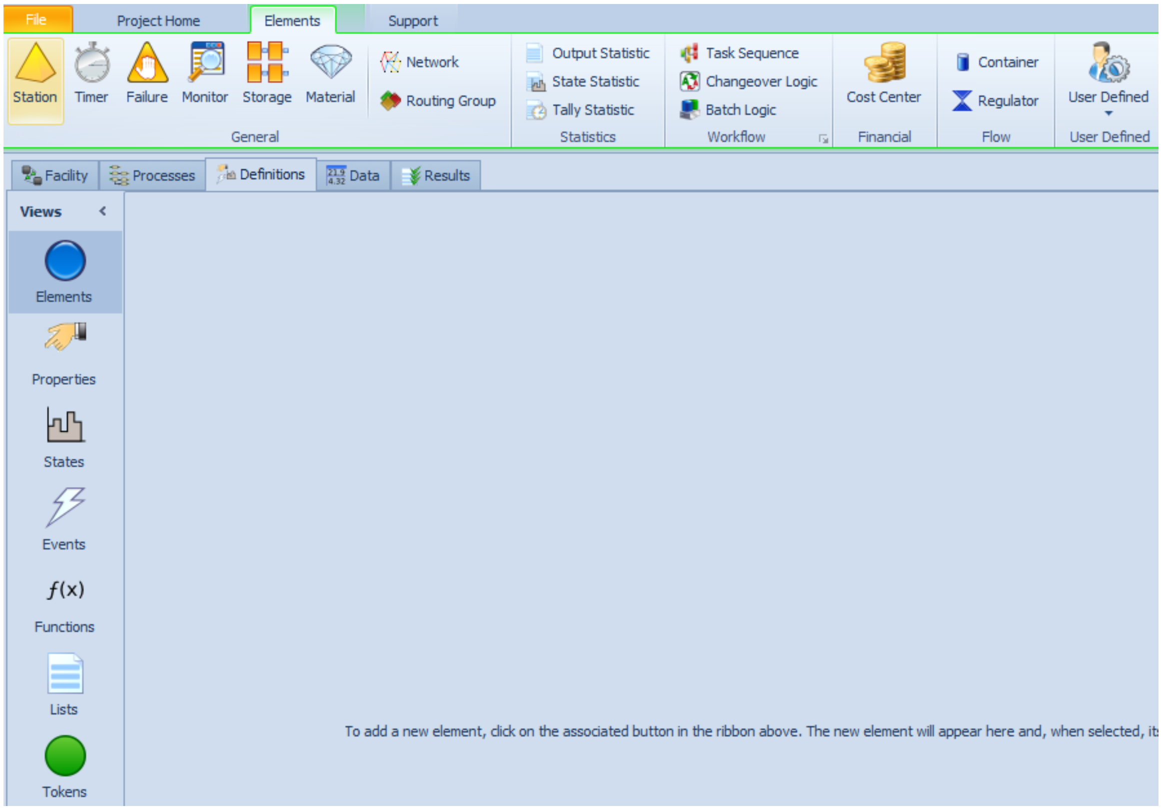


Figure 4.17 Simio's ability to interact with other models and software through events, functions and tokens.

4.6.2 Validation from a focus group of experts.

The validation of these scenarios, their feasibility and applicability were done through focus group interviews held at the University of Salford. Highways departments in the UK have different Tier1, 2 and Tier 3 contractors responsible for managing the road networks as well as constructing and maintain works. One expert from each Tier was available, and the simulation model was run in front of them to demonstrate its working and all available functions. It also presented them the data that was used, how it was collected and why different scenarios were chosen. Positive feedback was recorded from the experts.

All seven participants were welcomed and were briefed about the scope and need of this research work. They were also explained about the methods of data collection and how it was done step by step. After this, the researcher demonstrated the Discrete Event Simulation model on a computer to adequately explain its features, visual strengths, analytical abilities, the power to integrate other models and theories like lean and how different scenarios were performed and how they affected the operation's productivity. After the demonstration, they were asked various questions about the developed artefact and were also handed printed questions in the format of multiple choice questions and Rating from 1-5. Their responses about the accuracy is shown in the Figure 4.18 below.

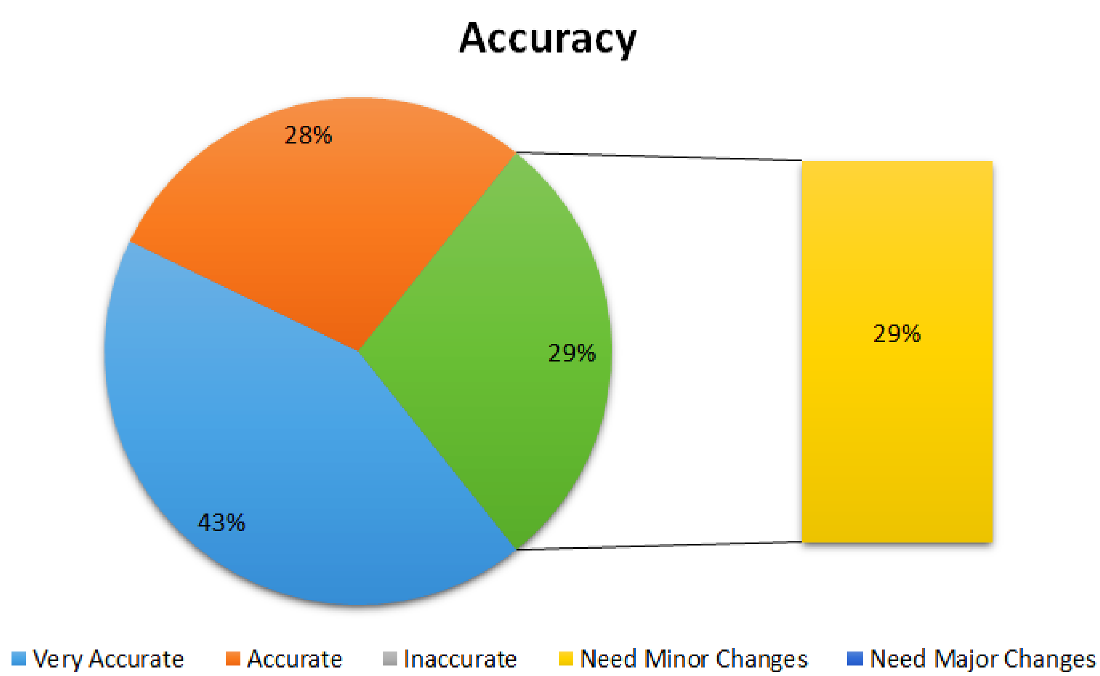


Figure 4.18 Response of focus group regarding the accuracy of the artefact.

When asked about the accuracy of the artefact, 43% of the participants agreed that it is "very accurate" and 28% said its "accurate" and depicted the actual operation in the computer environment. It not only involves the 3D graphical work but the ability to analyse the results, improve the utilisation of resources and to practice experiment that they cannot usually perform on-site. 29% of the experts believed that it needed minor changes and they were enquired about the nature of changes as well which are mentioned in the coming figures. The changes they mentioned were minor and will not affect the working of the simulation model. Some of these were modified accordingly and implemented in the model. However, some of these changes were out of the scope of this research work, and it was explained to the workshop participants in detail.

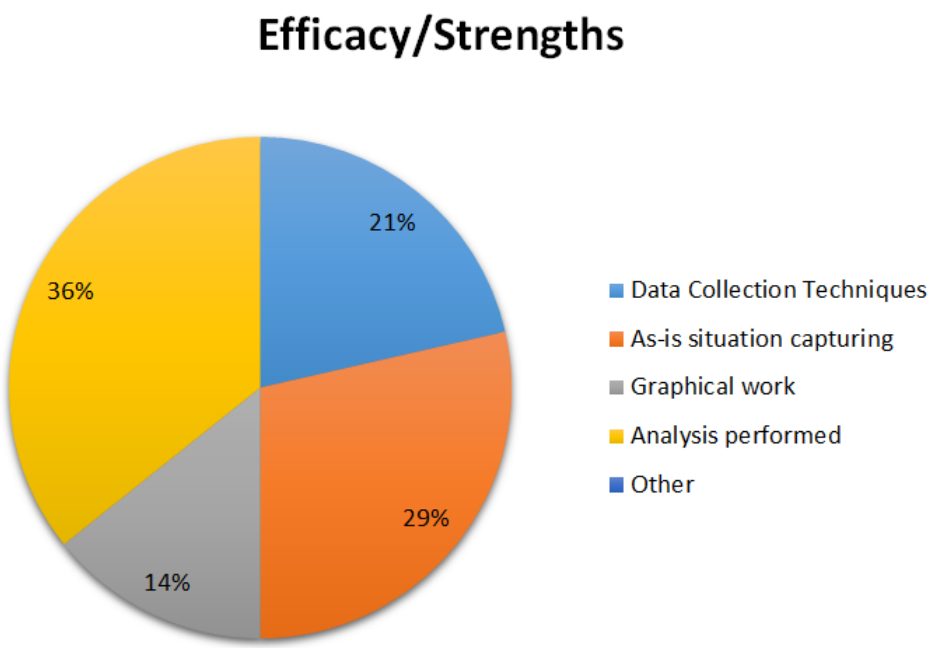


Figure 4.19 Responses of focus group about the Efficacy or key Strengths of the artefact.

After validating the accuracy of the model, its strengths were asked about from the experts. For the researcher, it might be efficient for reasons that carry no value for the industry and vice versa. Figure 4.19 above shows the response of their answers about the efficacy and the strengths of the artefact. 36% of the participants decided that the analysis performed using this model is its major strength and its ability to play various scenarios in a controlled environment reducing the uncertainty and enhancing the utilisation of all sorts of resources involved.

14% of the participants chose the graphical work and similarly other 21% through the data collection techniques, and the amount of data fed into the model was its vital strength. Discrete Event Simulation and especially, Simio have powerful 3D graphics that make the model more realistic and assists in understanding complicated processes with various sub-steps inside it

(Schriber, Brunner and Smith, 2018). 29% of the experts liked the as-is situation capturing ability of the artefact and how it mimics the real life operation.

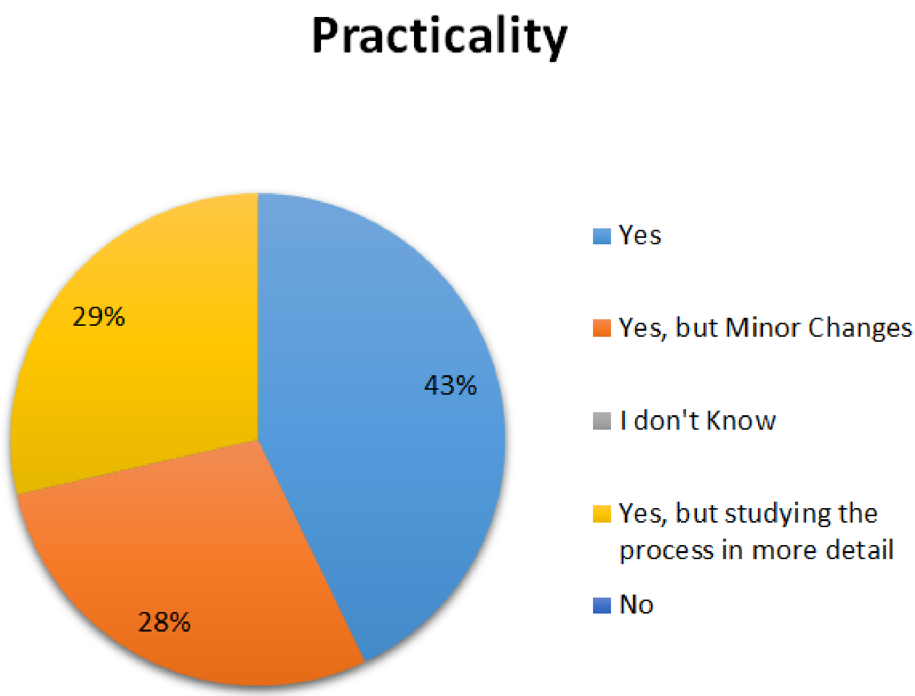


Figure 4.20 Response of focus group regarding the Practicality of the artefact.

The major purpose of this investigation was to develop simulation models that can are non-exclusive in nature and can be applied to other, similar projects around the world. Many people think that simulation modelling is an expensive and complicated task. However, they can efficiently use this model with the free version of the software used in this case to study their as-is process in detail, experiment different scenarios as needed according to the situation and improve the utilisation of their human and non-human resources.

Figure 4.20 above shows the responses of participants about the practicality of the artefact. During the technical evaluation, the practicality of the artefact was discussed numerous times. 43% of the experts, after looking at the working model of resurfacing operation, believed that the model is practical and can be applied to other, similar projects in nature. 28 % thought that some minor changes might be required like the addition of vehicles break down, realistic time for refuelling and the effect of break times etc. Remaining 29% said that it could be further improved after using it once on a different live project to get rid of any non-realistic assumptions.

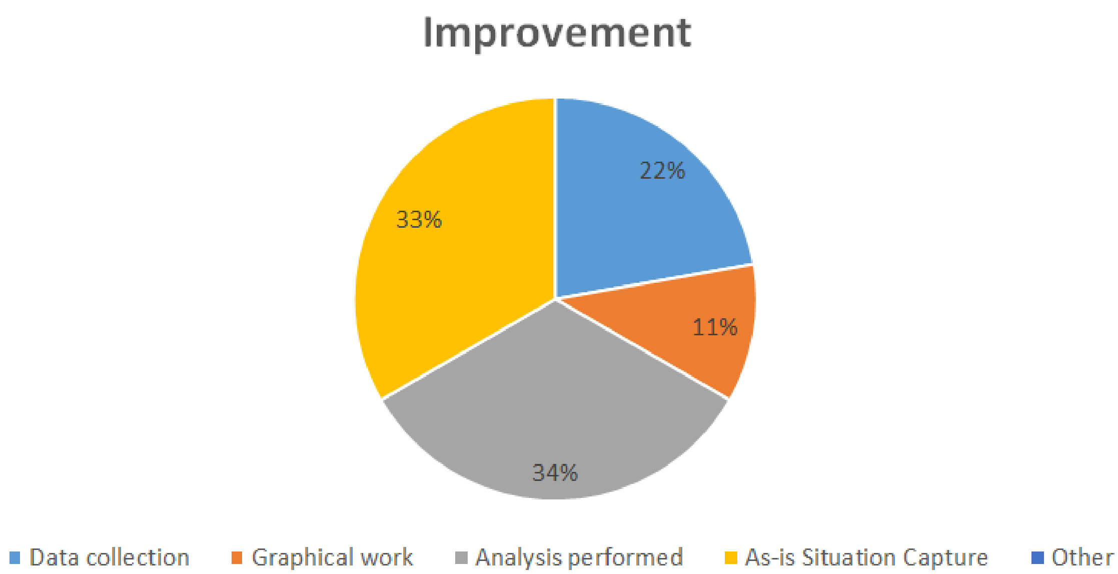


Figure 4.21 Response of focus group about the improvements required for the Resurfacing model.

In the previous question of about further required changes in Figure 4.20, 29% of participants thought it required further improvement and modifications to be fully functional and serve its purpose rightfully. The focus group experts were asked about the exact nature of the changes required, and their responses are displayed in Figure 4.21 above. 34% of these experts believed that the analysis work could be further enhanced and 33% thought as-is situation capture to be more efficient. The reason behind both of these was the inclusion of real-time traffic and weather data in the simulation model, which is easily possible. Simio has its own library of various atmospheric data providers for all over the world and traffic data can be used from google maps which are easily and freely available. Even though its method of inclusion has been mentioned in the simulation guide, it was not done by the researcher to keep it broad and not project-specific.

22% of the participants said that the data collection methods could have been further improved by looking into the amount of asphalt taken off the road and looking at factors like varying weather, its effect and other uncommon disruption. This could have been used to study the other process of asphalt recycling. It is a possibility for this simulation model that can be implemented, but it does not match with the scope of this research work. It is a great idea, but it would have required further time and effort for the data collection about the planing process as well. Some concern was expressed regarding shutting the additional lanes scenario number 4. It was suggested that it is not always possible to shut additional lanes as some roads are narrow lanes, have fewer lanes or are busier than usual routes. However, it is possible and is performed on motorways usually.

After the multiple choice questions, the participants were asked to rate the artefact using the guideline given to them. The purpose of this exercise was to perform sort of SWOT analysis of the artefact where different strengths, weaknesses, opportunities and threats can be identified by the data and then the participants can be asked about each of them in detail if required. Figure 4.22 on the next page shows the reliability analysis of the artefact. It shows that all the participants agreed that the combination of lean manufacturing and discrete event simulation had been applied appropriately to the resurfacing operation in this case. 86% of them also agreed on the process of data collection and how it was fed into the simulation model. Discrete Event Simulation modelling is micro level modelling which requires a lot of specific data for every step and sub-step in the process.

The experts appreciated the way this data was collected from reports, on-site observations and constant interaction with the industry partners. This is the reason that the assumptions made during the simulation development were realistic and did not deviate a lot from the reality. About 71% of the participants agreed that these assumptions were practical and will not cause the results to differ from reality. Majority of the participants agreed that the simulation and lean technique was applied during the right stage of the project, i.e. operation of execution stage as it involves most of the resources and consumes most of the budget. Most of the inefficiencies are usually found during this stage of the work that was also questioned during this research. They also agreed that other mathematical tools could not have presented the data in such form, perform different experiments and reduce uncertainty in the process like DES did.

When the experts were asked about the changes required and if they were major changes. Majority of them disagreed that the artefact required major changes but suggested various minor changes, out of which some were implemented straight after the workshop, and some of them were saved for future studies.

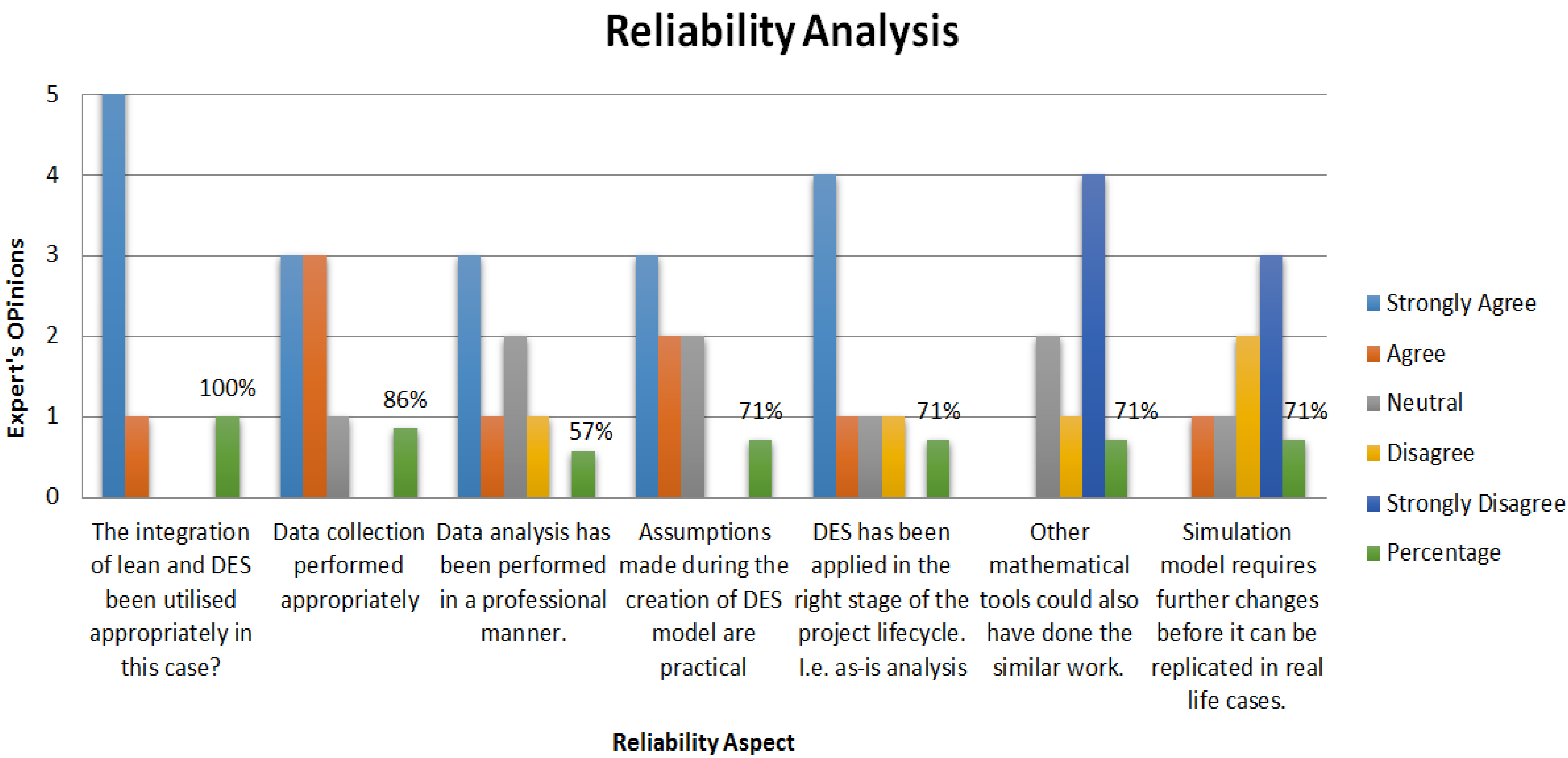


Figure 4.22 Feedback from focus group participants about the reliability of the DES model.

4.7 Discussion

The most significant activity in resurfacing operation is paving, where the paver machine lays asphalt on the road. It was noticed in the case study that paver was being used for only 2.5 hours out of the 8 hours' working window which reduces its efficiency to only 33%. It can be seen that paver utilisation can be maximised from 33% to 65% by implementing the integration of lean and simulation scenarios described above. In the UK, resurfacing operation is usually carried out overnight, and two lanes are shut for maintenance, and one paver operates in one lane at a time. During simulation trials, it was noticed that using two pavers in two different lanes is also a do-able scenario that can double the amount of work done at the same time.

The factors that can affect this experiment are weather, traffic volume, working styles and planning. The maximum paver efficiency achieved in the UK is 65% that was performed only once during the 1000-ton case study and has never been replicated afterwards. On the other hand, it is common to have more than 70% paver productivity in the USA due to different working window and working style. In California, the roads are shut for the whole weekend (55 hours), and alternatives are provided, but it pays off well at the end of the day (Qasim and Aziz, 2017a).

Well organised maintenance minimises the amount of time that a road has to be closed for repairs. Highways England has been trying to improve their process by adopting different approaches. However, the implementations are limited. For instance, the study carried out by (Andrew et al., 2015) experimented with Lean methods to maximise the resurfacing operation in the UK. The team managed to improve the process and laid 1000 tonnes of asphalt in one night compared to average 250 tonnes per night previously. However, even after a year, the 1000-tonnes target has never been replicated again; however, the daily average has risen from 250 to 600 tonnes.

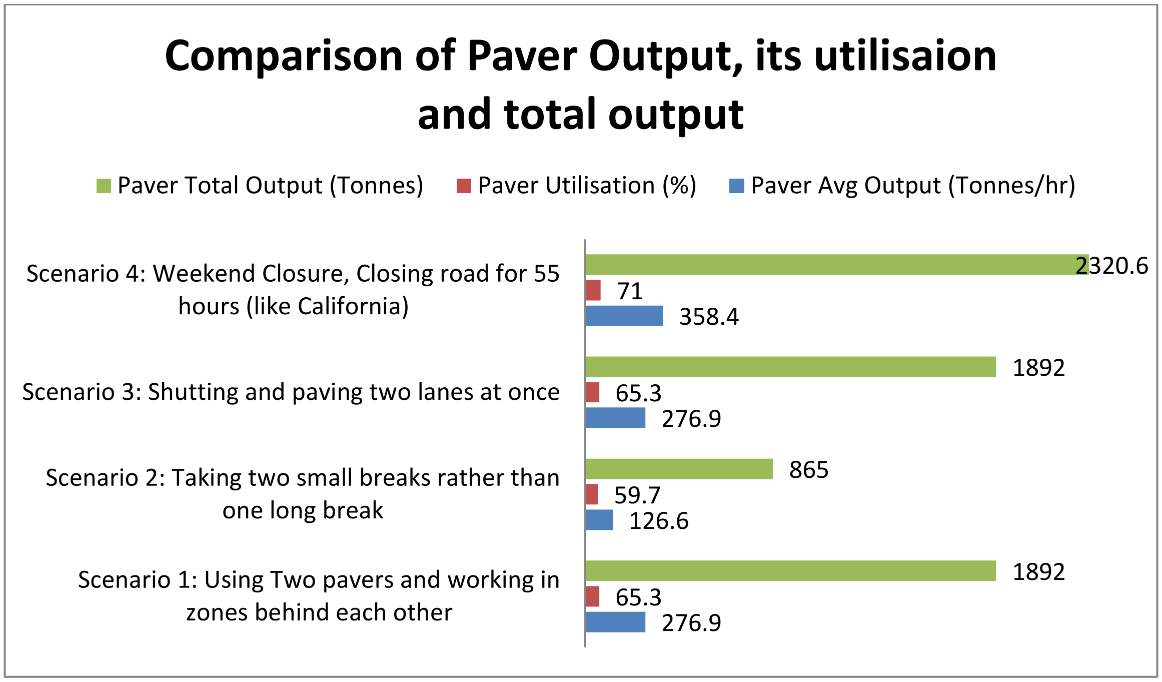


Figure 4.23 Comparison between paver output, utilisation and total output during the shift in one night.

Figure 4.23 above shows the comparison of paver's per hour output, its utilisation throughout the working window and total output during the shift. Paving is the most critical KPI for resurfacing as most of the Highways departments around the world calculate the productivity of resurfacing using the amount of asphalt laid per shift. Paver is used to put the asphalt on the road during maintenance and new construction processes; therefore, its efficiency matters the most during these operations. The figure above shows results from 4 different scenarios that were tested in the computer-based environment. The first scenario assumed using two pavers behind each other while dividing the road into two zones A and B as discussed in section 4.4.1. It involved two pavers simultaneously which automatically doubled the total output, however, the utilisation was also increased from 33% to 65% which is a significant increase.

The second scenario was experimented by changing the way the crew was taking breaks. In this case, machines were not turned off, and crew took breaks in two groups that also resulted in increased paver utilisation, i.e. 59.7% and the output was also increased from about 300 Tonnes to 865 Tonnes in one shift. This increase was because machines were kept running and operating throughout the working window and the break times did not disturb their activities. The third scenario was very similar to the 1st one where two pavers were used, however, in the

1st case; they were used in just one lane by dividing into two zones. However, in the 3rd scenario, they both were used in parallel on two lanes, not exactly next to each other. Therefore, the paver efficiency and the total output were found to be similar in both cases.

The last scenario was the most efficient out of the four. It was replicated using the data obtained from California's resurfacing rehabilitation of roads. In California, they shut the road where possible, for the full weekend, i.e. 55 hours. This allows the crew to work in different shifts of workers while the machines are still running and don't need to be turned off and transported to and from the plant. This saves a lot of time and effort that can be spent on the value-adding activities rather than unnecessary breaks and waiting. However, it cannot be applicable all the time due to the nature of the operation, the width of roads, permission to shut for the whole weekend and local laws and guidelines regarding this.

Figure 4.24 on the next page shows the overall cycle of the process that how the as-is process was first studied in detail and then simulated in the computer-based environment. Once it was modelled, it was used to experiment with various what-if scenarios that led to the improvements in the utilization of machinery and other resources. Finally, these scenarios can be validated and then implemented back into the industry.

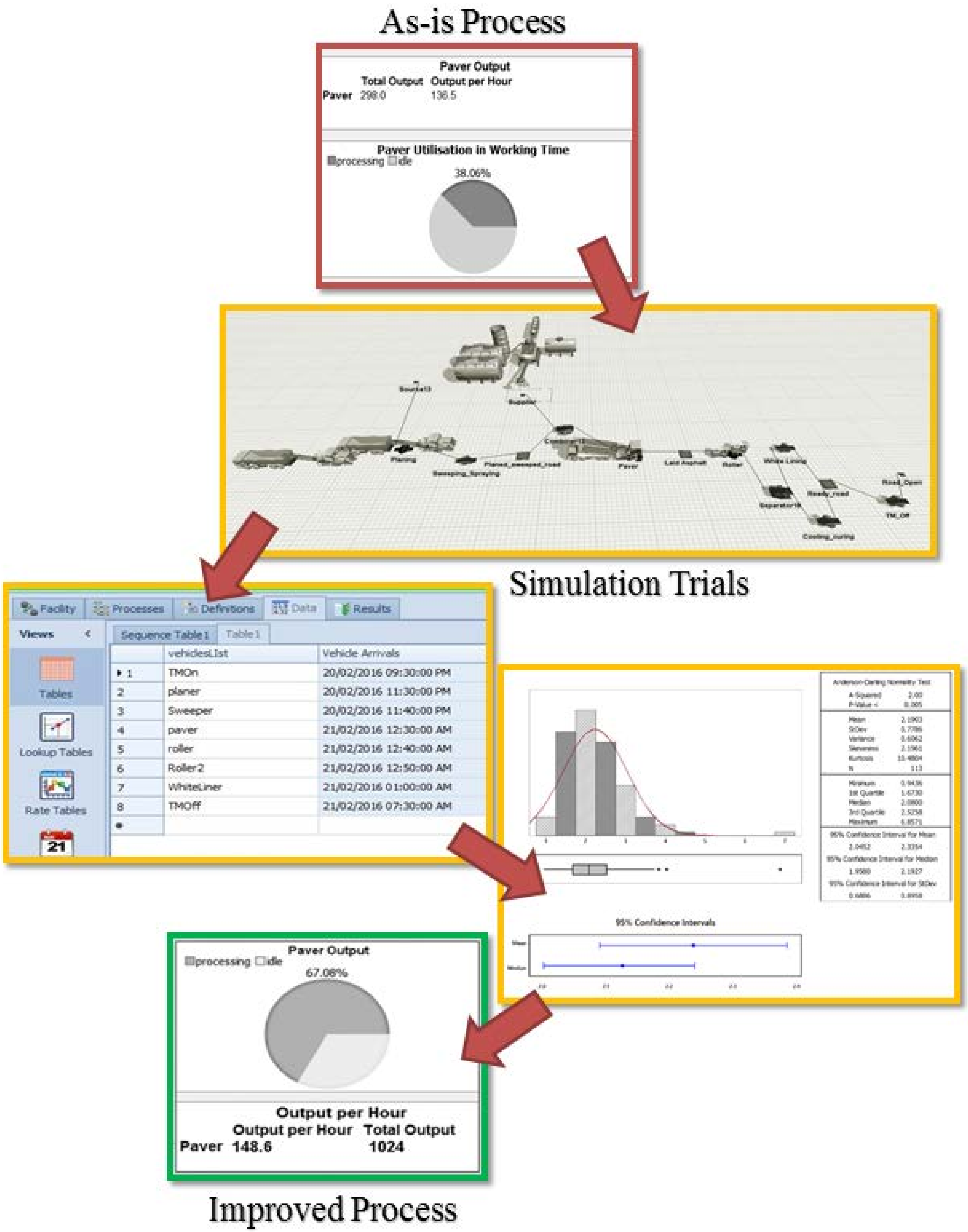


Figure 4.24 Advantages of simulation trials and how they can help in process improvement.

Chapter 5 : Case Study 2 Optimizing Earthworks with Discrete Event Simulation and Lean

Sections

5.1	5.2	5.3	5.4	5.5	5.6
Background of case study	Knowledge acquisition stage	Formalisation stage	Systemization and testing stage	Validation and refinement stage	Documentation and Implementation stage

Introduction

It is a complex task to schedule the earthworks involved in various projects. Different alternative scenarios in worksite layout and using various machine configurations have to be dimensioned and evaluated reliably. Any wrong decision taken at this stage will lead to uneconomic situations and delays leading to increased cost and project duration. Hence, it is vital to improve earthworks operations from initial stages till the end.

The planning stage of earthworks can be improved using discrete event simulation techniques. It can be done by measuring the performance of earthmoving machines and then strive to increase the performance using various scenarios. According to Wimmer et al. (2012), a simulation tool can also be combined with a mathematical optimisation model to minimise the transportation cost by reducing haul times. However, this wasn't performed at this stage due to limited time and resources.

Earthworks involve very few activities, personnel and equipment but consume a comparatively significant percentage of the construction budget. Earthworks deal with soil and digging which makes it critical to control the environment as well as production (time, cost and quality) issues. Various lean studies have been performed in the past to increase the performance of production and environment in construction (Belayutham, 2015).

Earthworks procedures include excavation of soil, its transportation and dumping using vehicles like dump trucks. It is a quite frequent and fundamental process in construction developments like building infrastructure, road paving and other civil engineering projects (Lin *et al.*, 2004). A substantial amount of work has been performed in this area over the last three decades which can be separated into 4 categories depending on their primary objectives. (Moselhi and Alshibani, 2009).

1) To improve the use of available resources like equipment and people involved in the project (Halpin and Riggs, 1992; Shi and AbouRizk, 1998; Marzouk and Moselhi, 2003; Lin *et al.*, 2004; Richard Smith, 2015; Aziz, Qasim and Wajdi, 2017).

2) To select the appropriate equipment according to the needs of projects that vary from project to project (Alkass and Harris, 1988; Jayawardane and Harris, 1990a; Marzouk and Moselhi, 2004; Moselhi and Alshibani, 2009; Nassrullah, 2016).
3) To reduce the cost of the work and complete earthworks operations within the target time frame (Jayawardane and Harris, 1990b; Ji *et al.*, 2010a; Liu and Lu, 2013).
4) To balance the utilisation of resources during the timeline of the whole project (Mayer and Stark, 1981; Said Easa and Asce, 1988; Jayawardane and Harris, 1990b; Ji *et al.*, 2010b; Kassem *et al.*, 2013).

This work, however, covers all four stages mentioned above directly or indirectly. The novelty is the on-site observation and data collection which feeds into the simulation model. This model can then answer various what-if questions to reduce the ambiguity that is not possible using lean or six sigma methods.

5.1 Background

Ambiguities and factors like changing weather may affect the productivity and performance of earthworks. These factors can disturb the schedule and cause delays in meeting the planned targets. To overcome such situations and save cost and time, work schedule is usually changed immediately based on present circumstances. During this process, the overall construction process is ignored. This flexible adaptation can, however, be modelled in the simulation environment (Wimmer *et al.*, 2012).

Simulating the earthworks processes is usually a complex and a challenging task. The necessary input data is often hard to collect due to access issues. The soil layers in construction areas are also estimated, and there is no accuracy in many assumptions, whereas, simulation modelling requires precise data. Sometimes on the construction site, the data required like transportation routes, the location of buildings, site equipment and other resources are stored in printed formats which are hard to access. The biggest issue is of data protection, and many companies are very reluctant to share even the most straightforward details about the work they are performing.

According to Wimmer et al. (2012), some uncertainties like weather conditions affect the performance of earthworks directly, but it is hard to measure and simulate. Such ambiguities cannot be reduced by using any method. However, in this case, study, the effect of weather has been recorded on-site, and it was noticed that the soil became harder with rain and the truck's speed was reduced to half to avoid slipperily. It is then possible to simulate both of these situations and study their result and then suggest some solutions.

Most of the optimisation work in earthworks has been done to improve the planning process. The scheduling aspect can complicate with time due to the fast pace of construction and the presence of several variables. The execution stage is that hardest part to simulate, and on-site conditions make the modelling more complicated and hard to control. However, this research work has been done by observing the on-site process and then developing a simulation model based on it.

"This undertaken project, to build a 4.5-mile new dual carriageway between Knutsford and Bowdon entered a new phase with re-routing of utility services around Bowdon roundabout and traffic management re-alignment along the existing A556, between the roundabout and Bucklow Hill" (Highways England, 2016).

A556 Scheme is located between Junction 19 of the M6 and Junction 7 of the M56. The work involved upgrade from a single lane to 4 lane carriageways. Following the installation of a new dual carriageway, the existing route would be transformed into a carriageway road. To achieve desired objectives, a typical improvement approach, namely DMAIC was adopted. The purpose was to define the scope of work, improve the efficiency of earth moving vehicles, improve the working style and perform various what-if optimisation scenarios with Earthmoving machines in a computer-based simulation environment, to minimise the impact on operations in real life.

At A556 site offices, Salford University research team arranged a series of meetings with the A556 project team and discussed existing processes and new opportunities for improvements within Earthworks processes. The A556 scheme involved moving of 1.1 million cubic meters of earth from excavation for road box and drain pipes, movement of soil, use of dumpers for transportation of soil, trim capping, laying base course and similar activities. Some key identified constraints and measures to mitigate them are shown in Figure 5.1 below.

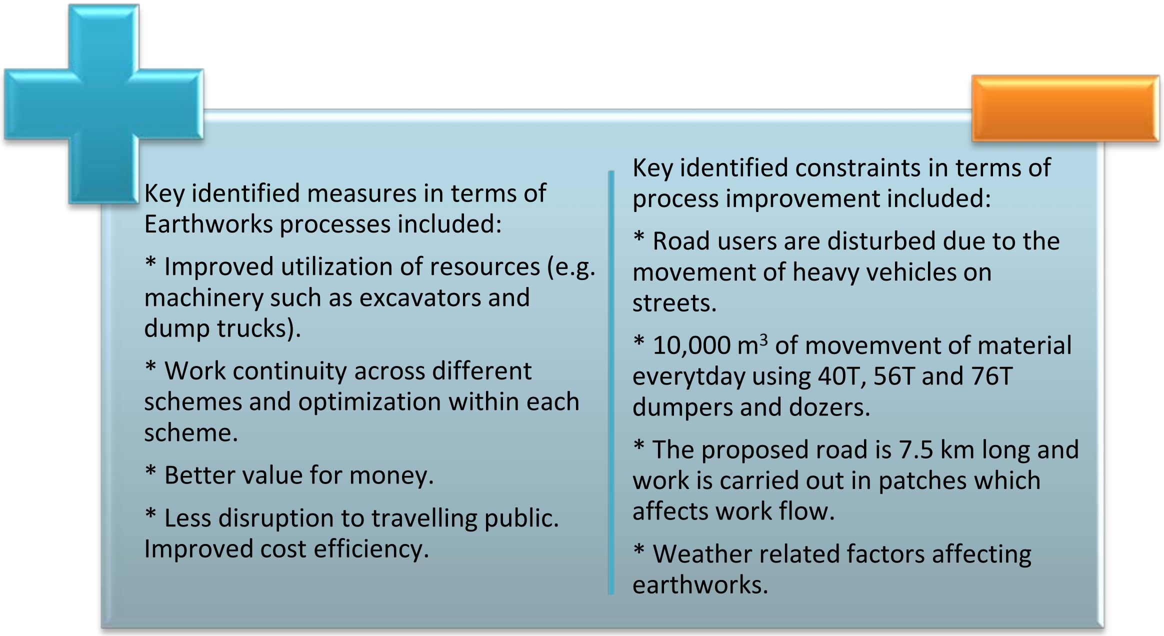


Figure 5.1 Opportunities and constraints in A556 case study.

Some of the significant constraints are weather-related effects which impact the productivity of machines and overall operations and to minimise the disturbance caused to the road users.

5.2 Knowledge Acquisition

Research team relied on original datasets provided by A556 team, supported by direct observations to verify the data and identify loopholes in practice. The work on the A556 scheme was divided into several different layers, and each layer was further distributed into patches. The reason behind this strategy was to avoid blocking any road or bridge that comes in the way and to apply lessons learnt from one patch to another. From a process improvement perspective, this gives an opportunity to investigate and improve one process in detail, and transfer learnings to next patch of work.

Various processes like excavation of road box, proof roll subgrade formation, LWD testing, and laying CBGM material, etc. were observed to capture data for simulation of the actual process to be developed, in a computer-based environment. Most of the data was provided by the Highways England's contractor, containing information about timelines, working hours, the sequence of activities, companies responsible for the work, their working style, their shift hours, duration of work and working windows. While, other data was captured at work sites on various days to get more detailed information about how earthmoving vehicles perform work, interact with each other and how their performance can be improved individually and overall as well. According to Martinez & Tech (1998), the data that is usually required to feed into the simulation system to analyse efficiently include geometry and location, ground conditions, equipment database and overall schedule. They are briefly explained in Figure 5.2 below:

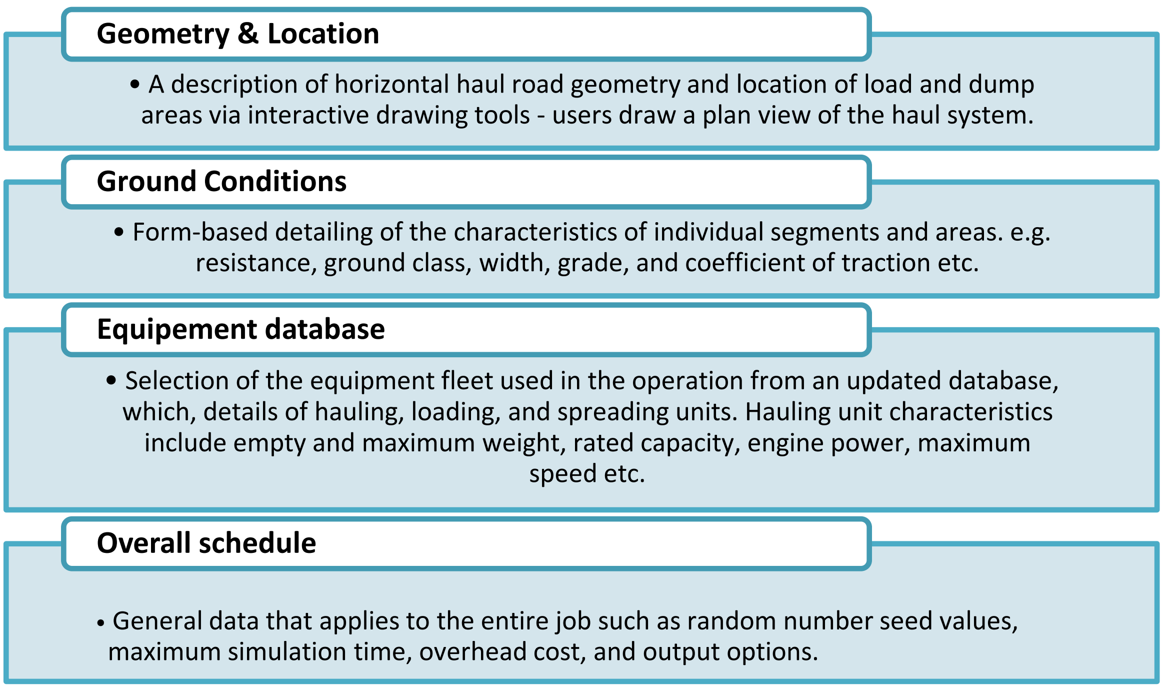


Figure 5.2 Necessary data required for simulation modelling in earthworks, Martinez & Tech (1998)

5.2.1 Identification of Problem

At this stage, the current or as-is process of earthworks was studied in this particular case, and various constraints were mapped. The first stage in simulation modelling is to thoroughly investigate the current process, eliminate any wastes and then suggest various improvement scenarios. At this point, two workshops were held at the work site and at Salford University where different stakeholders from client, contractor and sub-contractors were present. Various issues were raised ranging from machinery configuration to weather constraints, and some solutions were suggested as well.

Various process improvement opportunities were considered by stakeholders involved in this work, and it was helpful to have all of them on board to create a holistic approach to the process. The main aim was to increase the utilisation of the machinery, especially the excavator and dump trucks. This challenge was taken forward, and suggestions provided by the experts were later simulated in the computer-based environment. At this stage, the problem was understood, and a conceptual model was made which would be achieved in the final stages of the work.

The requirements for developing an earthworks simulation model are different from resurfacing. The layout, type of machinery, working hours and the health and safety issues differ from other cases. Figure 5.3 below displays some standard requirements for a planning tool in earthworks.

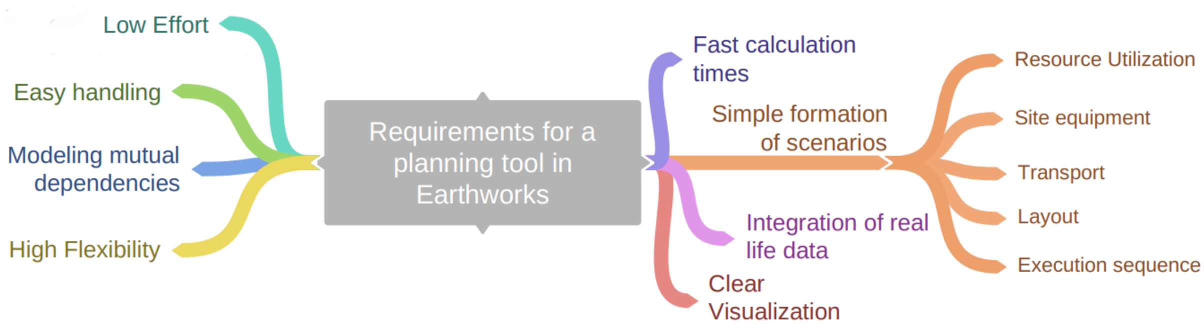


Figure 5.3 Requirements for a planning tool in earthworks (Source: TUM-fml).

5.3 Formalisation

Research teams engaged with stakeholders in different collaborative workshop sessions, to review findings and to discuss constraints affecting outputs and optimisation of resources and find possible improvements. One critical observation during simulation experiments was that productivity is significantly impacted on by the working style of the organisation and not so much by type of the machine. Using innovative technologies including modern machinery can positively impact productivity. However, the most substantial improvement opportunity lies in addressing traditional organisational issues such as matters related to procurement, contracting, recycling and collaboration

There is a lot of productivity related data produced by contractors and sub-contractors. However, its benefits are limited when it is not shared by the major stakeholders and also with Highways England (HE). No consistency in sharing efficiency related data is a constraint in achieving maximum productivity. Lack of available archival evidence and productivity records also hinder any improvement initiatives. Simulation studies approved the current design and arrangement of earth moving equipment by various contractors working with HE. Some issues are addressed by using the suggestions provided in this report.

The fundamental purpose of simulating the earthworks operations is to make sure that all construction activities are smoothly accomplished. Different uncertainties have to be identified so that they can be included in the model to improve the scheduling operations. The precise visualisation of construction operations is also a vital aspect apart from the economic issues. The majority of people find the 3d animation very useful as it provides an explicit representation of the site layouts, machinery types and works plans to avoid any misunderstandings.

Simulation modelling in earthworks can be applied in two different stages, i.e. work preparation and tender preparations. In tender preparations, construction processes are designed for short periods to calculate different costs before bidding. In work preparation, it is utilised to experiment with various scenarios and then compared together to create highly detailed plans (Wimmer *et al.*, 2012). Data provided by stakeholders, alongside data collected during site visits helped to develop a Discrete Event Simulation model. The reason for establishing a simulation model was felt to provide a safe working model for experimenting with various process interventions, without disturbing the actual process. Simulation development process involved simulating the as-is process, using collected data to identify any visible opportunities for improvements.

Once a simulation model has been developed, it was used to run various What-If improvement scenarios. Such exploration was not possible in real-world situations, because of the impact on ongoing construction processes. Different scenarios like changing the number of dump trucks, changing the number of excavators on one site, trying new routes to transport soil and testing new types of vehicles (tracked and wheeled) were trailed in a computer-based environment.

5.3.1 Lean Implementation

In this case study, different lean tools were used from the beginning of the project for its improved management and reduce any sort of waste in the processes. The work team utilised techniques like 5S (explained in detail in Section 2.5.2), visualisations performance boards, Obeya meeting areas and project control boards to improve the coordination and clarity of work. 5s is usually the initial lean approach in organisations to expedite the application of other lean methods which improve process parameters and overall structure. The combination of these techniques led to increased team coordination, focused meetings, increases meeting effectiveness, decreased meeting durations, identified bottlenecks and triggered useful discussions. Figure 5.4 below shows a sample of the Obeya meeting schedule and project board control on the right. This was taken during the data capturing process.

Figure 5.4 Obeya meeting schedules and project control boards used in this case study.

Modern tools and techniques like laser scanning, simulation modelling and data capturing can assist with the optimisation efforts and waste reduction. Figure 5.5 below displays how BIM models, project schedules and machines databases can be combined with simulation models to achieve accurate resource utilization, 4D visualisations and improved project schedules.

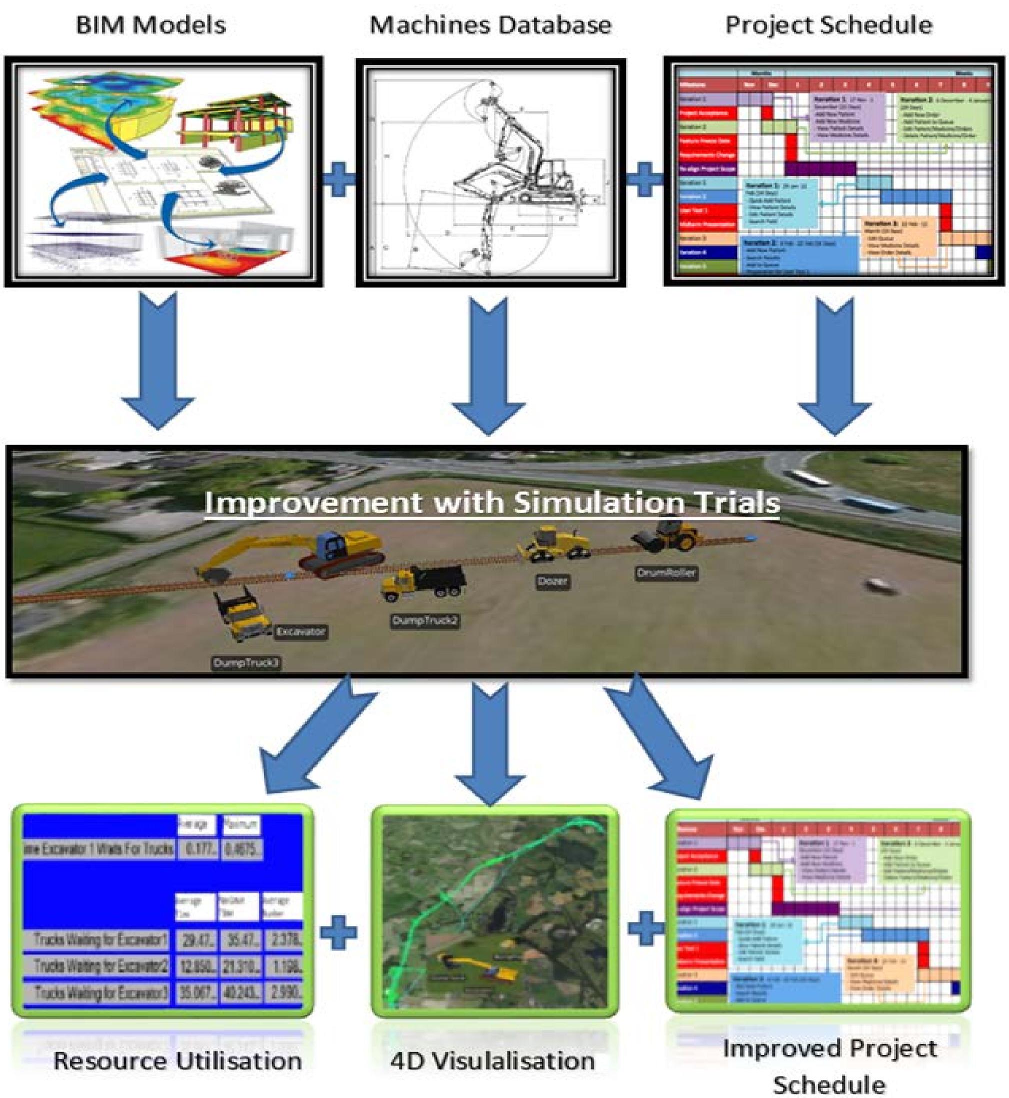


Figure 5.5 Interfaces of the simulation system used, Wimmer *et al.*, (2012).

5.4 Systemization and Testing

After collecting the relevant data, it was essential to define the boundaries of a simulation study. In this particular case, there were no major external factors that could influence the productivity of work apart from the weather. Since it is a typical cut and fill operation, therefore, the dump trucks were not using the public roads and were not affected by the traffic as well. After the simulation model was created, the current scenario was first studied using it.

5.4.1 As-is situation analysis

To improve a particular process or activity, it is first mapped manually for understanding the constraints and factors affecting the productivity. After some of the issues have been resolved manually, it is then simulated in a computer-based environment. The earthworks process at A556 scheme was simulated in software called Simio. The as-is situation was based on the data collected by the author himself at the construction site. Different sub-activities were recorded with sturdy cameras to analyse them later.

At this step, the contractors use 1 excavator and 4 dump trucks to move the soil as part of the cut-and-fill operation. When the current process was drawn in the computer-based environment, it was seen that the excavator has been the busiest entity and was choked for most of the time. Figure 5.6 below shows the simulation model of earthworks. It also presents the utilization of various machines in the user interface for better visualisation and understanding.

Figure 5.6 Simulation model of earthworks case study in Simio.

The Table 5-1 below shows the utilisation of different machines and critical performance indicators that are used to calculate the performance. It can be observed that the average waiting time for each truck at the excavator is about 5-6 minutes, which means that the dump truck has been waiting in the queue for average 5 minutes during each cycle. This reduces the utilisation of trucks and makes it only 46% average (for all 4 vehicles). In this particular scenario, the distance between the excavator and the dumping point was 1 km. Excavator seems to work for 99.98% which is not possible in real-life and means that it has been choked with excessive tasks of digging the soil and loading the trucks while moving 1m forward after every 5 minutes.

Table 5-1 showing the results of the as-is situation in earthworks on a usual day

Parameter	Result
Excavator Efficiency	99.98 %
Excavator Total waiting time	0.00144 hrs
Average waiting time for each truck at the excavator	0.0925 hrs
Truck average Utilisation	46.155 %
Trucks total distance covered by all trucks	133.52 km
Distance btw Excavator and Dumping point	1 km

Table 5-2 showing list of variables in as-is Scenario

Variables in this Simulation Scenario: 1					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
1	4	1km	5-7 km/hr	40 tons	8 hours

5.4.2 Scenario No. 1: Effect of weather, slow speed of trucks and slow excavation, speed 1m/s instead of 2 m/s

This scenario focussed on assessing the effect of weather on the movement of dump trucks and how it impacts the excavator utilisation and the overall operation. In normal circumstances, when the weather is clear, the dump trucks travel at an average of 5-7 km/hr has the terrain usually muddy and uneven. However, when it rains heavily, the soil becomes mud, and the loaded dump trucks find it difficult to move at the same speeds. The speed of trucks under such circumstances is reduced to half to maintain the safety of the truck and the driver.

Interestingly, since the speed of trucks is reduced, they take more time to reach the excavator and the excavator is not choked anymore and the trucks utilisation is also improved. However, the average duration for trucks waiting at the excavator is increased from 2 minutes to 4 minutes. This scenario (reduced speed due to weather) is seen more commonly in the earthworks as the weather is mostly rainy in the UK and this is the reason that contractors use this configuration of excavators and dump trucks, i.e. 1 excavator and 4 trucks. Table 5-2 below displays the results of this scenario.

Table 5-3 showing the results of scenario 1 in earthworks case study

Parameter	Result
Excavator Efficiency	88.62 %
Excavator Total waiting time	1.2511 hrs
Average waiting time for each truck at the excavator	0.0667 hrs
Truck average Utilisation	63.24 %
Trucks total distance covered by all trucks	117.52 km
Distance btw Excavator and Dumping point	1 km

Many environmental factors can seriously impact the safe operation of a haul truck. Haul roads can have different properties on dry days compared to wet days and become very slick when wet. Snow may also impact the available traction or increase braking distances (Department of Health and Human Services, 2015). For this reason, it was essential to study the effect of weather conditions on the speed of dump trucks and then how it will impact the overall procedure by influencing the utilisation and idle times of excavator and other vehicles.

To do this change in the model, there are two options. First is to define the weather as constraints in the simulation system which will determine the new behaviour of the vehicles. The second and more straightforward way of doing is to see how the weather impacts the speed (from archival data and on-site observation) and then use this decreased speed as the average speed of the trucks. Figure 5.7 below shows the properties tab in Simio that was used to define the travelling speed of the vehicles to experiment with this scenario.

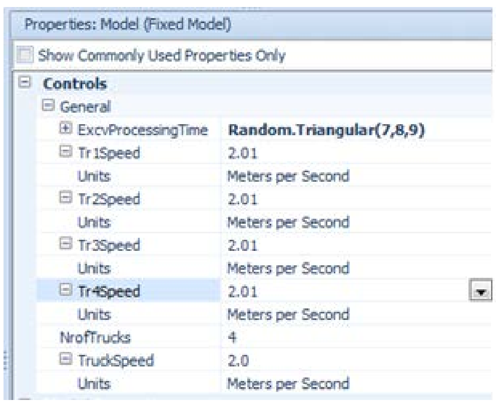


Figure 5.7 Properties tab for the Vehicles to change movement speeds.

Table 5-4 below shows the different variables that were changed for this scenario testing.

Table 5-4 showing list of variables used in Scenario 1

Variables in this Simulation Scenario: 1					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
1	4	1km	2.5-3.5 km/hr	40 tons	8 hours

5.4.3 Scenario No. 2: Changing the length of soil dumping point

Earthworks mostly involve cut and fill operations where the soil is removed from a higher point and then dumped on the lower grounds to make the surface even for further construction work. The lengths of dumping point may vary each day and on each project. It is also possible that the dumping location can be several miles away from the excavation point and it can take hours for the transportation of soil. This can adversely impact the utilisation of excavator and the crew members at the digging area. If the distance between those two points is doubled (from 1km to 2km), the excavator total idle time increased from 1.2 to 1.9 hours and the excavator utilisation is also slightly reduced. Table 5-3 below shows that changing the length from 1km to 2 km does not affect the utilisations as much. Therefore, it has been modified once more to understand the effects in detail.

Table 5-5 Results of scenario 2 in earthworks case study.

Parameter	Result
Excavator Efficiency	82.29 %
Excavator Total waiting time	1.948 hrs
Average waiting time for each truck at the excavator	0.0489 hrs
Truck average Utilisation	64.47 %
Trucks total distance covered by all trucks	244.92 km
Distance btw Excavator and Dumping point	2 km

If the length is further increased to 4km, which is not an unusual scenario at work sites, it means that the dump trucks have to move 2 km from one point to another to get rid of the soil and cover the same distance on its way back. The results of this scenario can be seen the Table 5-4. Now the efficiency of the excavator is profoundly affected and is reduced from 99% to 43% and the truck total waiting time is increased from 0.0015 hours to 6.17 hours. It means that the excavator has been working for only half of the shift time because the total shift time is 12 hours and after removing 1-hour break, it is 11 hours and out of these 11 hours, 6 hours are wasted in waiting for the next available truck.

The efficiency of the excavator is more important than of the dump trucks as the trucks are shows working even if they are in travel, waiting for the excavator or are loading and unloading. However, the excavator is like a processor in this case which is controlling these trucks and is affected by them as well.

Table 5-6 Results of scenario 2 in earthworks case study.

Parameter	Result
Excavator Efficiency	43.83 %
Excavator Total waiting time	6.177 hrs
Average waiting time for each truck at the excavator	0.0730 hrs
Truck average Utilisation	66.59 %
Trucks total distance covered by all trucks	275.5 km
Distance btw Excavator and Dumping point	4 km

Figure 5.8 Side view of 3d modelling of earthworks pilot project below shows the 3D side view of the earthworks machinery. Instead of leaving the data tabs in the results chamber, they were also pasted in the main interface window to record the effect of any modifications on the system.

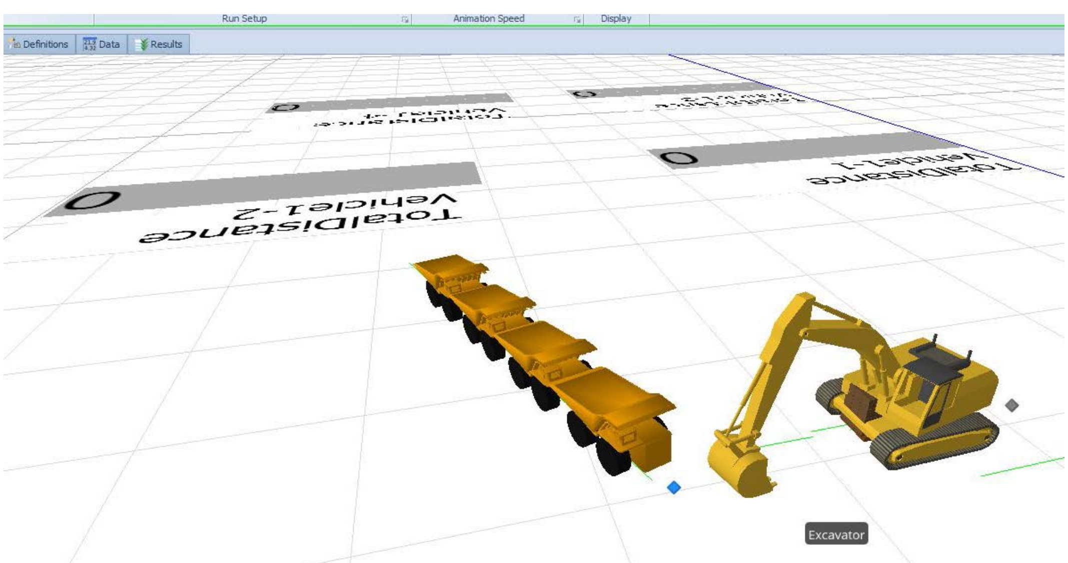


Figure 5.8 Side view of 3d modelling of earthworks pilot project.

Table 5-7 showing list of variables used in Scenario 2

Variables in this Simulation Scenario: 3					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
1	4	1 km and 4 km	5-7 km/hr	40 tons	8 hours

5.4.4 Scenario No. 3: Changing the type of trucks

During the interactions with industry, one point which was after raised was to experiment with different kinds of trucks in terms of capacity. Most of the earthworks sites use 40 Tonne dump trucks and this case study involved the same. It takes about 7-9 minutes to fill a 40T truck entirely and by changing the weight / capacity of the truck, the processing time would also increase accordingly. Table 5-5 below displays the results of this scenario where the truck types are modified.

Table 5-8 Results of scenario 3 in earthworks case study.

Parameter	Result
Excavator Efficiency	99.98 %
Excavator Total waiting time	0.00144 hrs
Average waiting time for each truck at the excavator	0.0925 hrs
Truck average Utilisation	46.155 %
Trucks total distance covered by all trucks	133.52 km
Distance btw Excavator and Dumping point	1 km

Table 5-9 showing list of variables used in Scenatio 3

Variables in this Simulation Scenario: 3					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
1	4	1km	5-7 km/hr	80 tons	8 hours

5.4.5 Scenario No. 4: Changing the number of excavators: 2 excavators with 2 trucks each

The fourth scenario that was performed to improve the earthworks process was to increase the number of excavators from 1 to 2. Since the cut and fill operation involves a lot of digging and the excavator has to load the soil in trucks simultaneously, it was suggested by the industry colleagues that having two excavators (rather than one) can be a game changer.

The number of dump trucks or other resources was not changed. Since the earthworks task is performed by a subcontractor, and the experiment could prove expensive by bringing a new excavator and then record the performance, it was simulated as well. Here the results are practical, and none of the machines is choked or present bottlenecks.

The average waiting time for trucks waiting at the excavator was reduced from 5 minutes to 1.3 minutes, which means that trucks utilisation was also increased from 46% to 83%. Trucks usually wait for one minute at the excavator before loading starts as it has to position itself precisely below the excavator's arm. The amount of soil dug was also doubled because the number of excavators was doubled more distance was covered by the excavators than before. (Before it was 100m each day, after adding an extra machine, it went up to 200m approx.

In Table 5-6, it can be seen that excavator waiting time has increased dramatically; however, it does not mean that the excavator has been standing idle, but it has been digging the soil while no truck was around. In the as-is scenario, the trucks were waiting for the excavator to load soil, but it was busy in digging the ground.

Table 5-10 Results of scenario 4 in earthworks case study.

Parameter	Result
Excavator 1 Efficiency	70.76%
Excavator 2 Efficiency	71.13%
Excavator 1 Total waiting time	3.21 hrs
Excavator 2 Total waiting time	3.17 hrs
Average truck waiting time at excavator 1	0.0265 hrs
Average truck waiting time at excavator 2	0.01665 hrs

Table 5-11 showing list of scenarios used in Scenario 4

Variables in this Simulation Scenario: 4					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
2	2	1km	5-7 km/hr	40 tons	8 hours

5.4.6 Scenario No. 5: Changing the number of excavators: 2 excavators with 3 trucks each

One can argue that by doubling the number of excavators, they were starving (waiting idly) for significant time periods. Therefore, in this scenario, the number of trucks was increased from 4 to 6. This means that each excavator can work with 3 trucks each. After running the shift for 12 hours, including 1 hour's break, it was seen that the excavator efficiency again went up to 99% and waiting times for excavators were reduced to great extent. However, the truck utilisation was affected as well. It jumped from 83% to about 64% as it can be seen in Table 5-7 below.

There are various factors like weather, surface conditions, and people's behaviour which can further affect the productivity of the overall process as well as the performance of each machine. The weather and speed of vehicles were mapped in the simulation model. However, other factors were ignored for the purpose of simplicity.

Table 5-12 Results of scenario 5 in earthworks case study.

Parameter	Result
Excavator 1 Efficiency	99.62%
Excavator 2 Efficiency	99.66%
Excavator 1 Total waiting time	0.042 hrs
Excavator 2 Total waiting time	0.037 hrs
Average truck waiting time at excavator 1	0.0265 hrs
Average truck waiting time at excavator 2	0.0661 hrs
Truck average Utilisation	63.77 %
Distance btw Excavator and Dumping point	1 km

Table 5-13 showing list of variables used in Scenario 5

Variables in this Simulation Scenario: 6					
Number of excavators	Number of dump trucks	Distance between excavator and dump point	Speed of dump trucks	Size of dump Trucks	Shift duration
2	3	1km	5-7 km/hr	40 tons	6 hours

5.4.7 Effect of length change between the excavator and dumping point.

To study the effect of changing lengths between the cut and fill point, the distance was changed four times ranging from 1km to 4km. This means that the trucks will have to travel this much distance in each case before it comes back to the excavation point. Figure 5.9 below shows four different graphs including, clockwise, the excavator efficiency, the time that the excavator waits for trucks, the average duration that trucks wait for excavator and the trucks average efficiency. It can be noticed that the excavator efficiency and trucks efficacy behave inversely. It is because when the distance increases, the trucks take more time to travel which keeps them busy in simulation terminology, but the excavator has to wait for more extended periods now. An additional truck can be added when the distance increases to stabilise the system to minimise the waiting time and wastage.

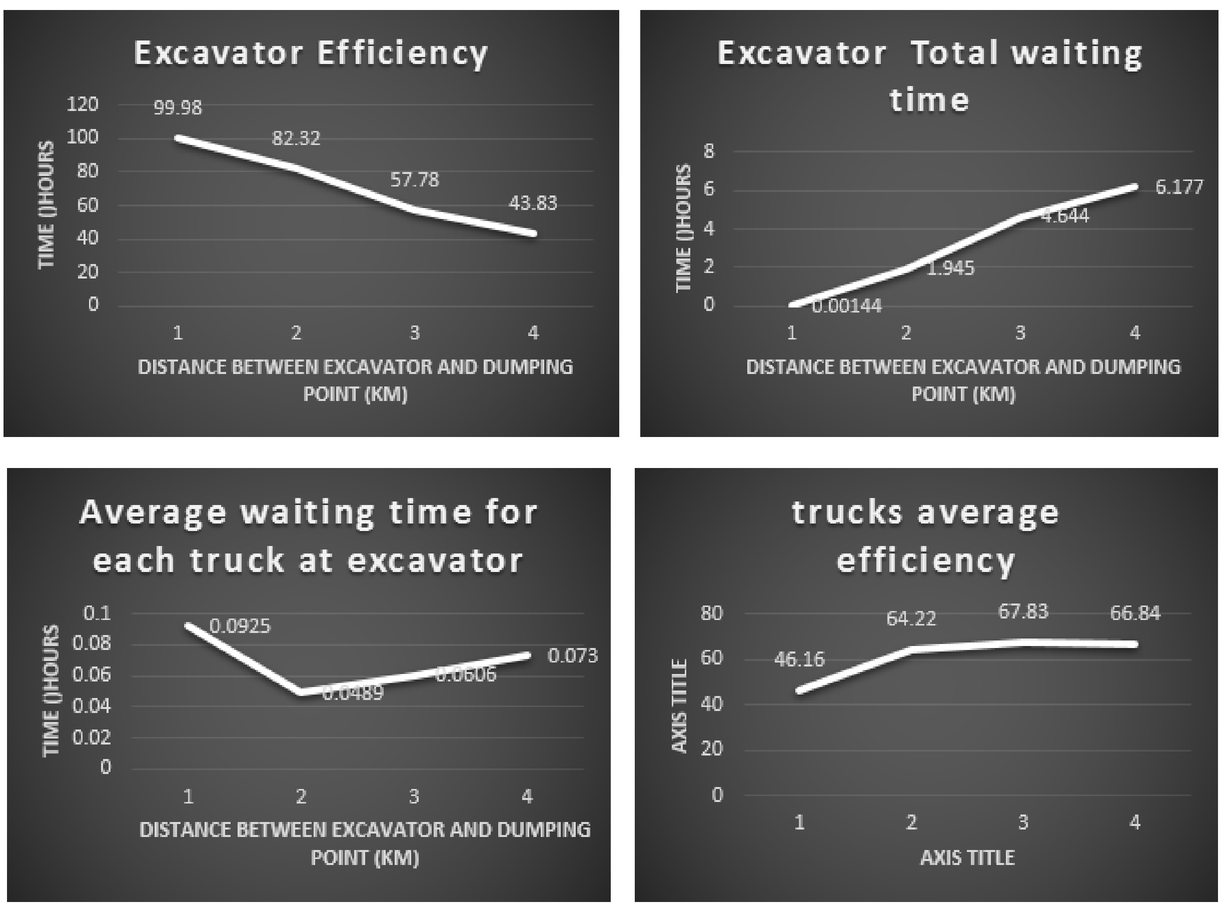


Figure 5.9 showing the effect of haul length on excavator and truck's utilisations

5.5 Documentation and Guideline

5.5.1 Modelling of Current State

In this simulation project, the aim was to understand the current state of an earthwork operation and its performance in various what-if scenarios. The best and most optimized situation was also identified at the end. Software called Simio was chosen for this analysis because of its powerful animation and experimental capabilities.

a. Excavator and Dump Trucks

The current state of the system consists of 1 excavator and four trucks with 40 tonnes load capacity each. During initial research, we found that 1m^3 of earth equals to 1.4 tonnes of earth. Therefore it was calculated that each truck has 28.5 m^3 of earth capacity. It was also identified that the load capacity of the excavator's bucket as 1.5 m^3. Therefore calculations showed that an excavator has to load 28.5/1.5=19 buckets to fill a truck. From the video recordings collected from the work site, it was found out that loading of each bucket takes about 25 seconds. Therefore, loading of one truck takes around 25*19=476 seconds or 7.9 minutes. To make the system more realistic, a triangular distribution was chosen for excavator processing time as a triangular distribution with parameters; minimum: 7, median: 8, maximum: 9 minutes. This processing time of excavator equals to the loading of one truck. The capacity of the excavator and the trucks are set to one. Therefore, each processing of one model entity which is "pieceofearth" will equal to one load of the truck.

b. Model Entity and Source

The model entity is named as "piece of earth" which is intended for the use of one truckload of the earth in the model. The symbol "Pallet" is applied to this entity which has a brown colour and cubic shape to give a similar look to one truckload of the earth. On the "Generate Earth" source item, the entity to be generated was chosen as "pieceofearth", and an initial number in the system was set to 2. Triggering event for generating new entities is chosen as

Output@Excavator so that each time an entity "piece of earth" exits the excavator, a new "PieceofEarth" will be created. Therefore the system will never run out of earth source, and there will be no excess entities in the system that will slow the simulation. "Generate Earth" source item is connected to Excavator by a connector so that each new entity created will be present at excavator in no time.

c. Trucks, Nodes and Paths

In the initial state of the system there are 4 trucks, but since in the what-if scenarios the number of trucks will vary, one vehicle item is dragged into the system called Vehicle1, an initial number in system value is set to 4 under Population properties of Vehicle1. Unloading time of Vehicle 1 is set to 1. Since loading time is integrated in the processing time of the excavator no value for loading time is assigned to vehicles. The initial desired speed of the vehicle is set to 2.01 meters/sec which corresponds to 4.5 miles/hour.

Initial node (home) of the Vehicle1 is set to Output@Excavator so that vehicles will start the simulation at this location and idle action is set to Park at Home so that vehicles will return back to their starting location after they unload the entity they carry. In order to enable to logic of transportation of the "PieceofEarth" by the vehicles, in the Output@Excavator node, transport logic was set to "Ride on Transport", and since there is only one vehicle object in the system with a population of four, transporter type is set specific and Vehicle1 is selected in the transporter name option. Reservation method was chosen as first available at the location.

The unidirectional path from Output@Excavator to Sink is created, and another unidirectional path from Sink to Output@Excavator was designed so that the vehicles driving in the opposite direction will not cause a deadlock in the transportation network. Initial travel mode of the vehicle was also set to Network only for the Network based model and to free space for free space model. For the free space model, no paths have been created.

Finally, since the excavator loads earth directly into trucks, the vehicle should be assigned as a secondary resource to the excavator. For this reason, the Excavator is modelled as a Workstation, and secondary resource is set as Vehicle1 as seen in Figure 5.10 below. By, doing this assignment excavator cannot start working/loading without a truck being present at Output@Excavator node.

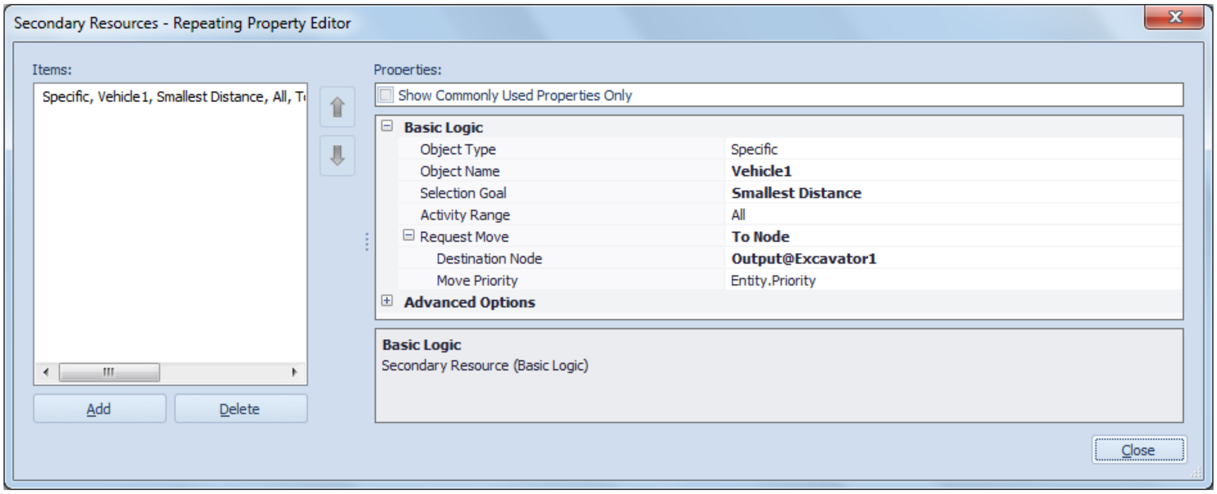


Figure 5.10 Excavator secondary resource as trucks.

d. Status Label Animations

In order to follow the utilization rates and other KPI's such as average waiting times and total travelled distance of trucks during the simulation run, it is required to add status label animations in the model window.

- The utilization rate of the excavator is calculated by following formula; "Excavator1.ResourceState.per cent time (1)".
- Average waiting time at excavator Is calculated by following formula; "Excavator1.Output.ParkingStation.Contents.AverageTimeWaiting"
- Total Distance travelled by Truck1 is calculated by following formula; "Vehicle1[1].total distance travelled / 1000"

e. Experimentation

In order to do experiments in Simio, first, control parameters have to be defined. In this particular case, the parameters are defined as a number of trucks, the speed of trucks and excavator processing time. In order to add these inputs as control parameters, developers right clicked on the name of each of these inputs and chosen Set Referenced Property, and then Create New Referenced Property option from the list. Each of the Referenced Properties was named corresponding to the name of the input, such as “Excv1ProcessingTime” for the processing time of the Excavator1 and “Excv2ProcessingTime” for processing time of Excavator2 and so on as seen in Figure 5.11 below. Same steps were repeated for the Number of Trucks for Vehicle1 and Vehicle 2 and speed of Vehicle1 and Vehicle2.

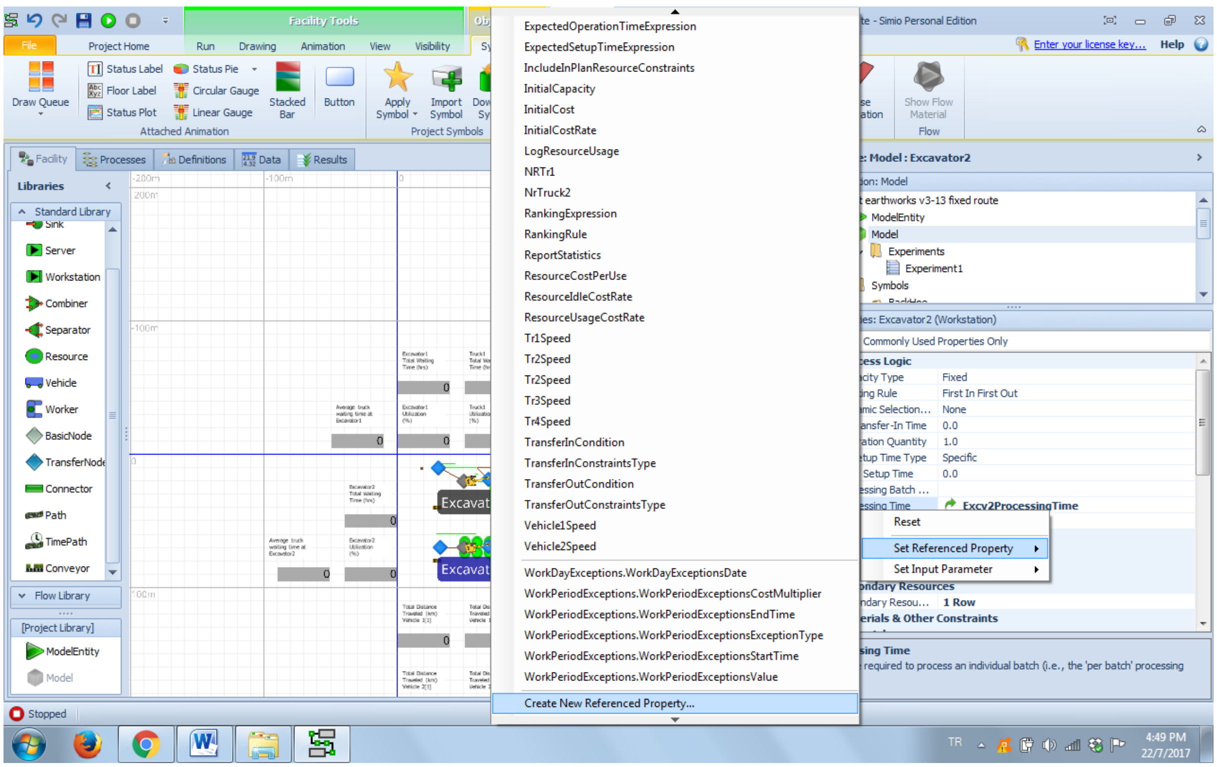


Figure 5.11 Setting Control Parameters for Excavator Processing Time.

Once all the control parameters were defined, a new experiment was created by right-clicking the model entity in the browse menu and selecting create new experiment option. In the experiments window one can see the control parameters defined before, but the responses of the system have to be defined as well which corresponds to the KPI’s of our model, so that once someone changes the value of a control parameters, they will see the change in the value of KPI’s such as utilization and total distance of trucks. This will help in understanding the outcome of various what-if scenarios according to the given inputs.

In order to see the value of our KPI's for each scenario, one needs to assign them as responses in the experiments window. In order to do that, they can click on Add Response button. First, they can directly input the name of the response, and in the expression field, they can copy the function created for animation of this KPI in the model window. For instance, we name the response Excv1Utilization and enter "Excavator1.ResourceState.per cent time(1)" formula for the utilization rate of the Excavator1 as seen in

Figure 5.12 below.

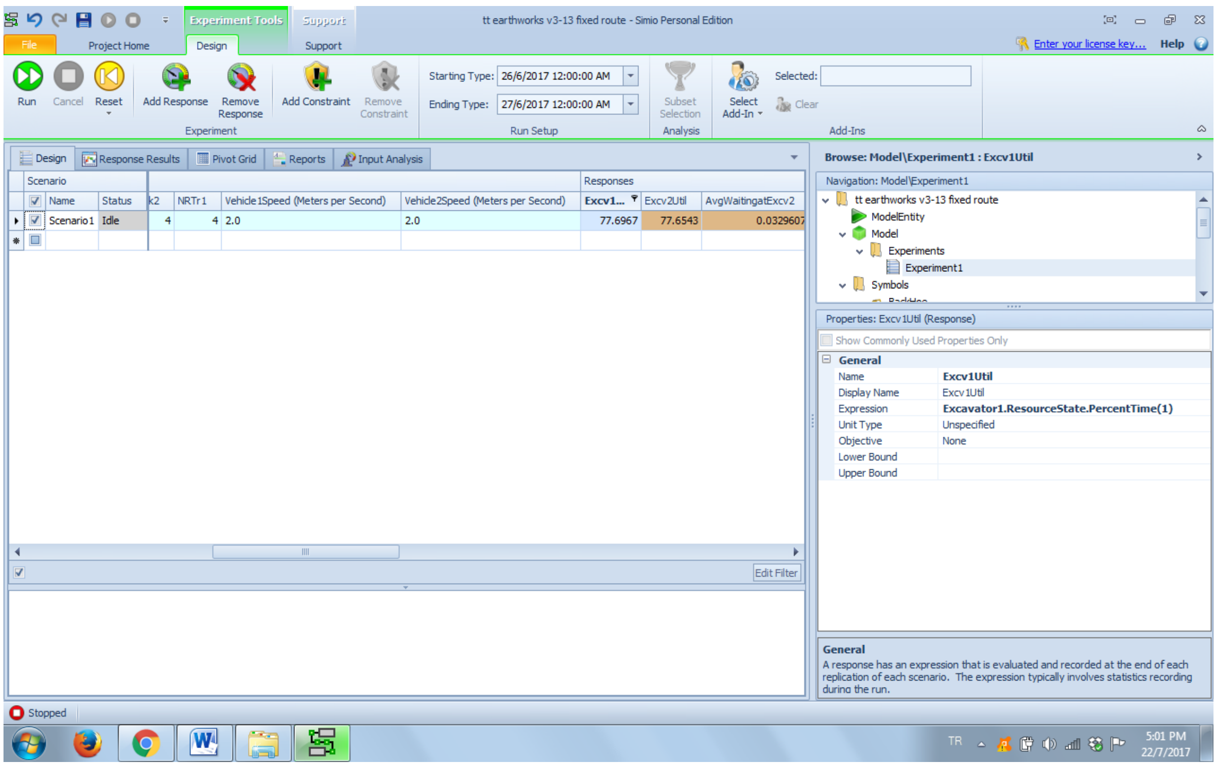


Figure 5.12 Adding responses to experiments.

Same steps were applied for all of the responses wanted to investigate the average waiting time at excavator and total distance travelled by each truck. Now, any value for our control parameters can be entered at this stage (i.e. Excavator processing time distribution, Number of trucks and speed of trucks) and see the result of our responses (i.e. utilization rate of the excavator, average waiting time at excavator and total distance travelled by each truck) for each scenario.

f. Moving Excavator Model

For the moving excavator model, the aim is to move the excavator one meter to the east, (closer to sinking) each time it loads a truck. In order to do this, an add-on process trigger was added on Excavator Exited in the Add-on process triggers properties of Excavator1. The name of this process is “Output_Excavator_Entered” for Excavator 1. Next, under the Processes tab, one is able to see the process that will be used for this triggering event (entity exiting output@excavator1 node).

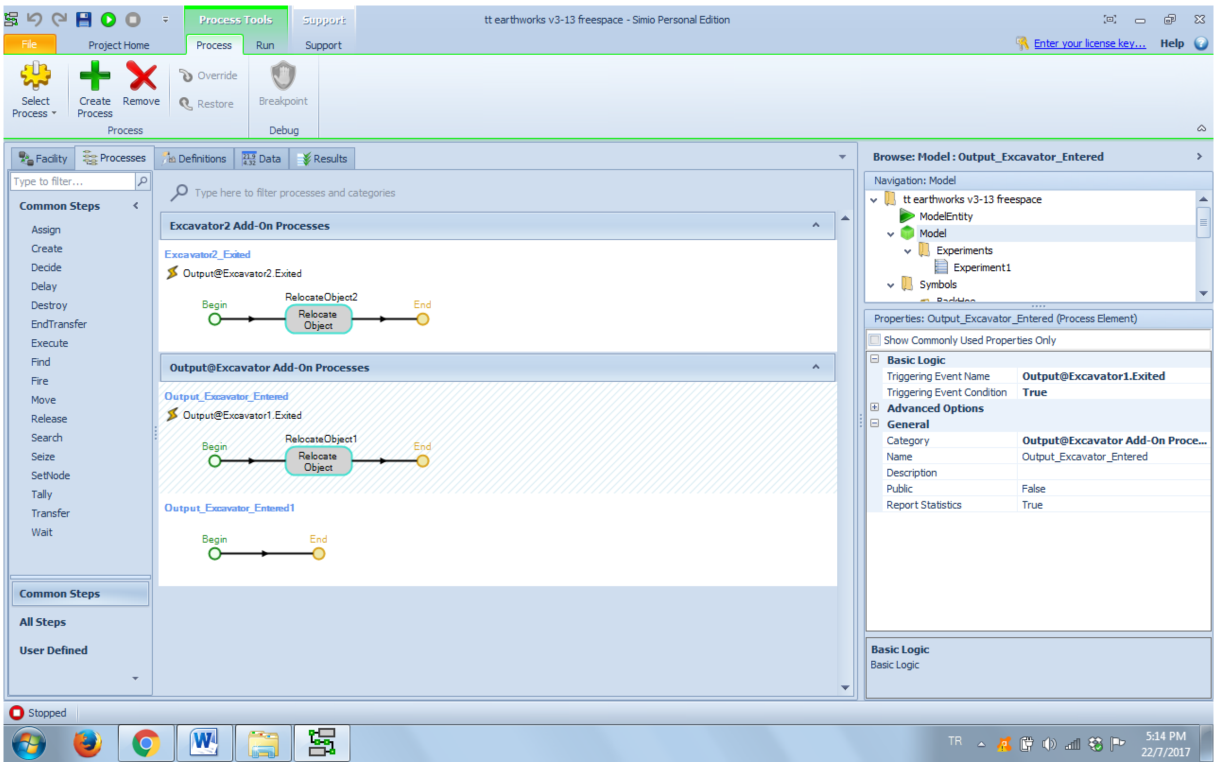


Figure 5.13 Excavator Add-on Process Trigger.

In the properties of the process, event name was chosen as Output@Excavator1.Exited and Triggering condition True. So, each time an entity exists Output@Excavator1 node this process will be triggered.

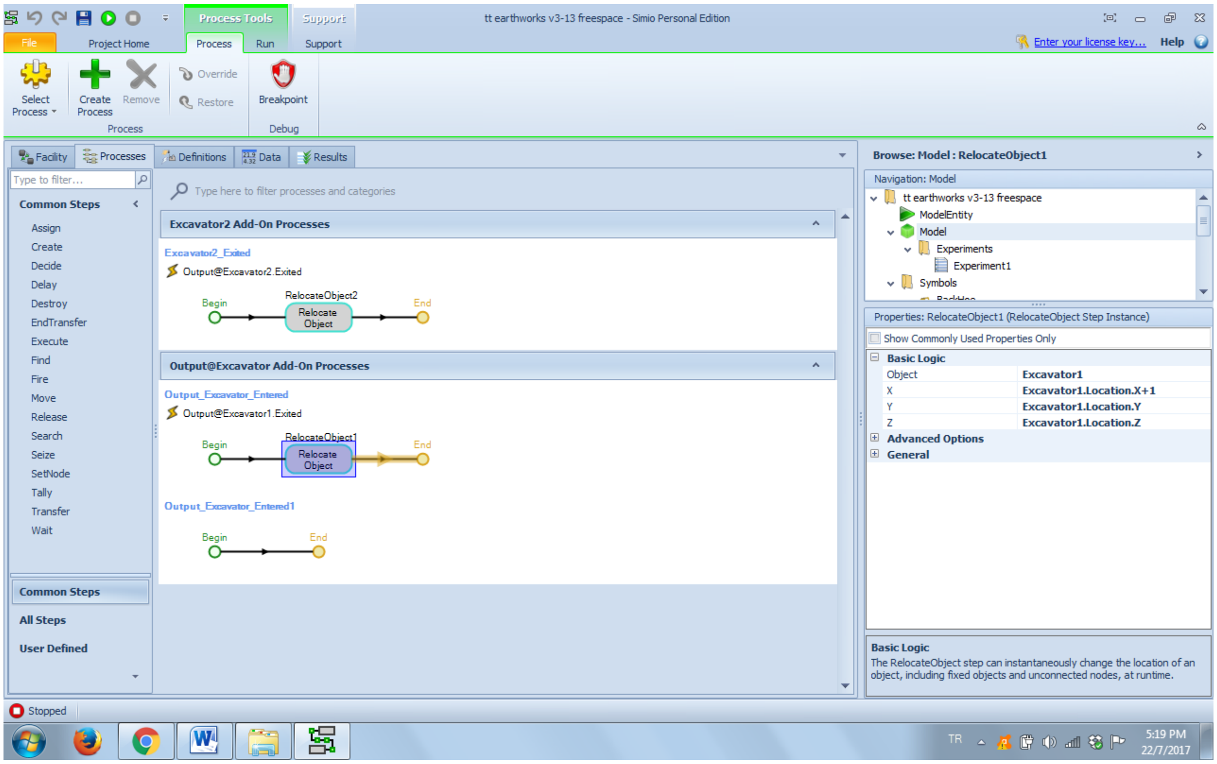


Figure 5.14 Relocate Object step properties.

Next, a single step was added called "Relocated Object" from the User-defined menu as seen in Figure 5.14 above. The author chose the object to relocate as Excavator1 and new coordinates of this object to; for x, the current x coordinate of the Excavator1 object +1, for y, current y coordinate for the object and for z, current z coordinate of the object. By doing so, Excavator1 moves 1 meter to the East each time it completes loading of a truck. The same logic is applied to Excavator2 for two excavator model.

5.6 Validation

The technical validation of the model was performed using the initial data captured for the experimentation. After that it was also tested using artificial (made up) data that could predict the outcomes easily and explain if the model is working properly. The validation of this artefact (simulation model and its guidelines) was performed in two stages:

1) Validation through the theoretical artefact evaluation process
2) Validation from a focus group of experts.

5.6.1 Validation through the theoretical artefact evaluation process

Firstly, the artefact (simulation model and recommendations based on it) was validated using the hybrid method designed by Prat et al. (2014) which is also shown in Figure 5.15 below. This method is based on a theoretical checklist that acts as a rigorous testing method for newly developed solutions or artefacts. In order to respond to this, the answer is divided into 5 main dimensions as shown below. The main system dimensions it includes are the goal, environment, structure, activity and the evolution of the artefact. Each aspect is then further divided into criteria and sub-criteria for a clear breakdown of an artefact into visible parts. The dimensions are comprehensive regarding evaluation criteria and further sub-criteria to ensure the developed artefact is functional, precise and useful.

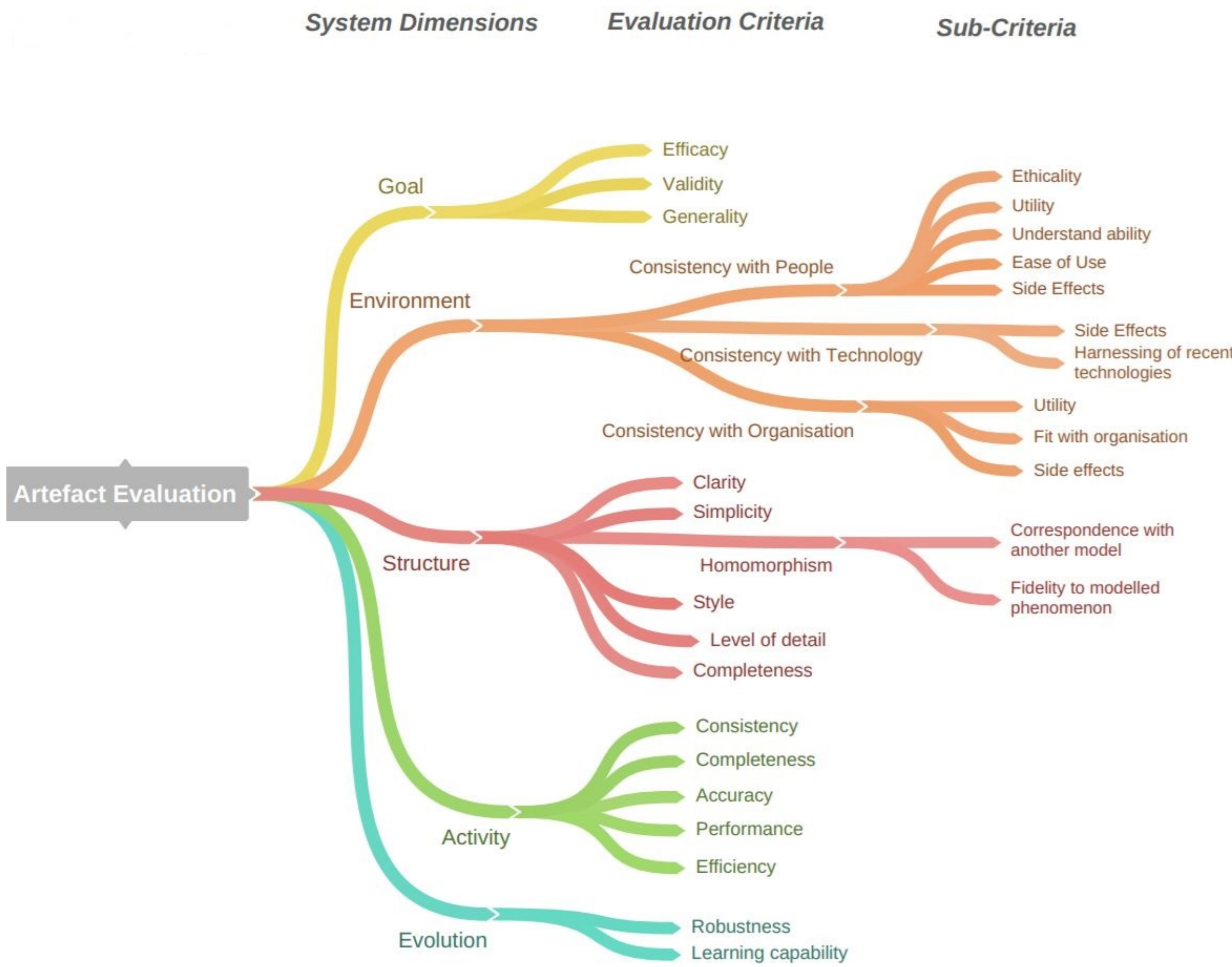


Figure 5.15 Hierarchy of Criteria for Artefact Evaluation, Prat et al. (2014)

5.6.1.1 Goal

The end goal was to improve the as-is process of earthworks operations that was accomplished by simulating various earthworks scenarios, understanding them in detail and then explore multiple what-if situations to determine the most fruitful one. These scenarios were suggested by the industry partners as they couldn't experiment these in real life due to time and budget constraints. The developed Artefact (simulation model and its recommendations) is efficient because it fulfilled the initial aim of this case study, i.e. to reduce waste and improve the speed of work.

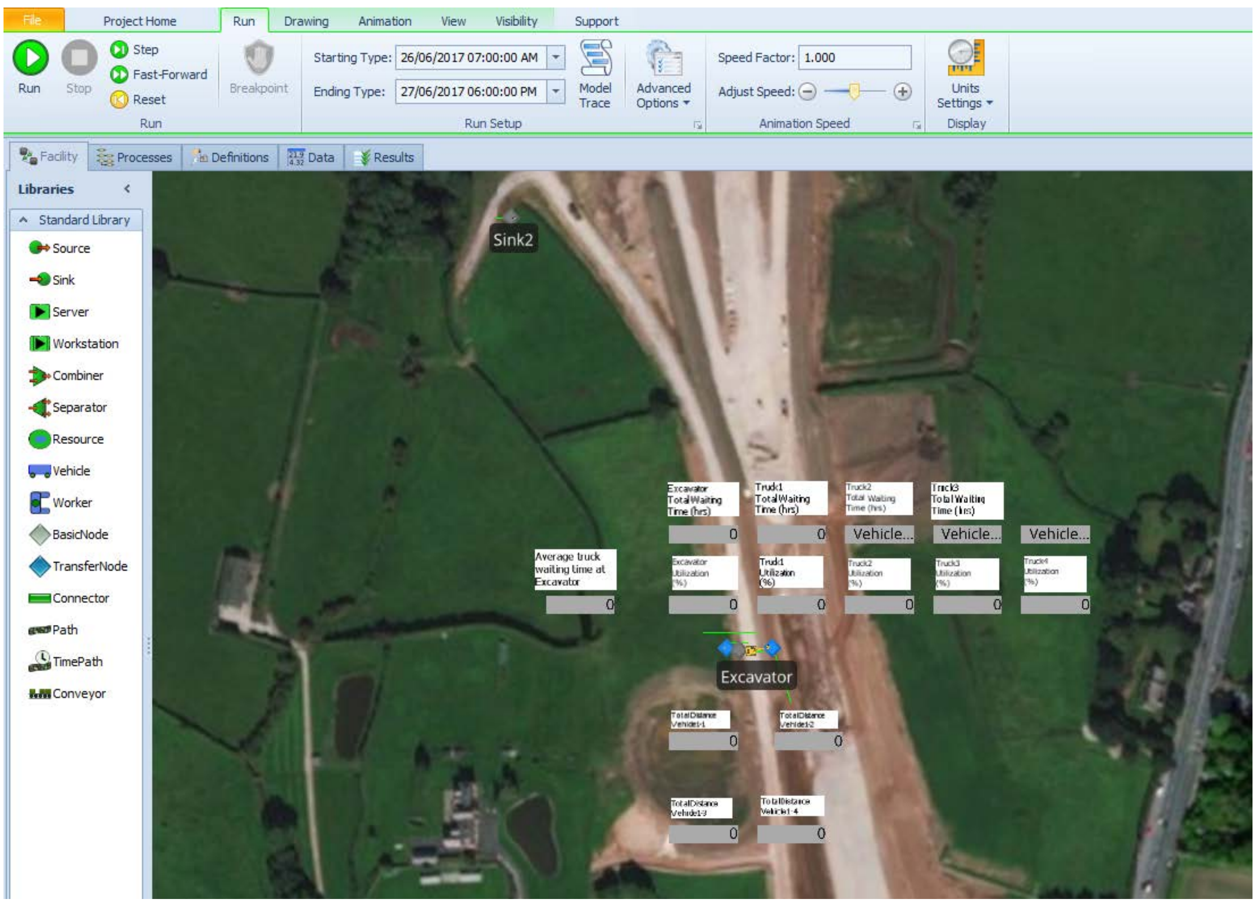


Figure 5.16 Main interface of Earthworks case study in Simio software placed on real location using GIS.

Tens of runs have confirmed its validity in the computer-based environment and during the workshop by experts. The developed solution ticks the generality box as well due to its applicability in all earthworks scenarios, different lands and layouts, a different set of machinery used, changeable weather constraints etc. It can also be applied to almost any country in the world as well as the method and machinery for digging and transporting soil is similar across the globe. Figure 5.16 above shows the main interface of the Simio software where this simulation model was produced. This model was constructed using the exact location of the case study with the help of GIS. This made it easier to locate the cut and fill points and estimate the distances between them. It also assisted in deciding the speed of vehicles based on different terrain types like mud, greenery or roads.

5.6.1.2 Environment

The environment in this aspect means an organisation, people involved and the machinery being used (Hevner et al. 2004). The developed artefact should establish its consistency with these three viewpoints. Regarding consistency with the organisations, the utility of the developed simulation model responds thoroughly. Majority of construction firms responsible for Earthworks are perpetually keen to advance their construction processes to maximise resources utilisation and hence profit. They can adopt the guidelines and the simulation model itself to understand the hidden data behind operations, effects of various constraints, identify waste and diminish it as much as they can.

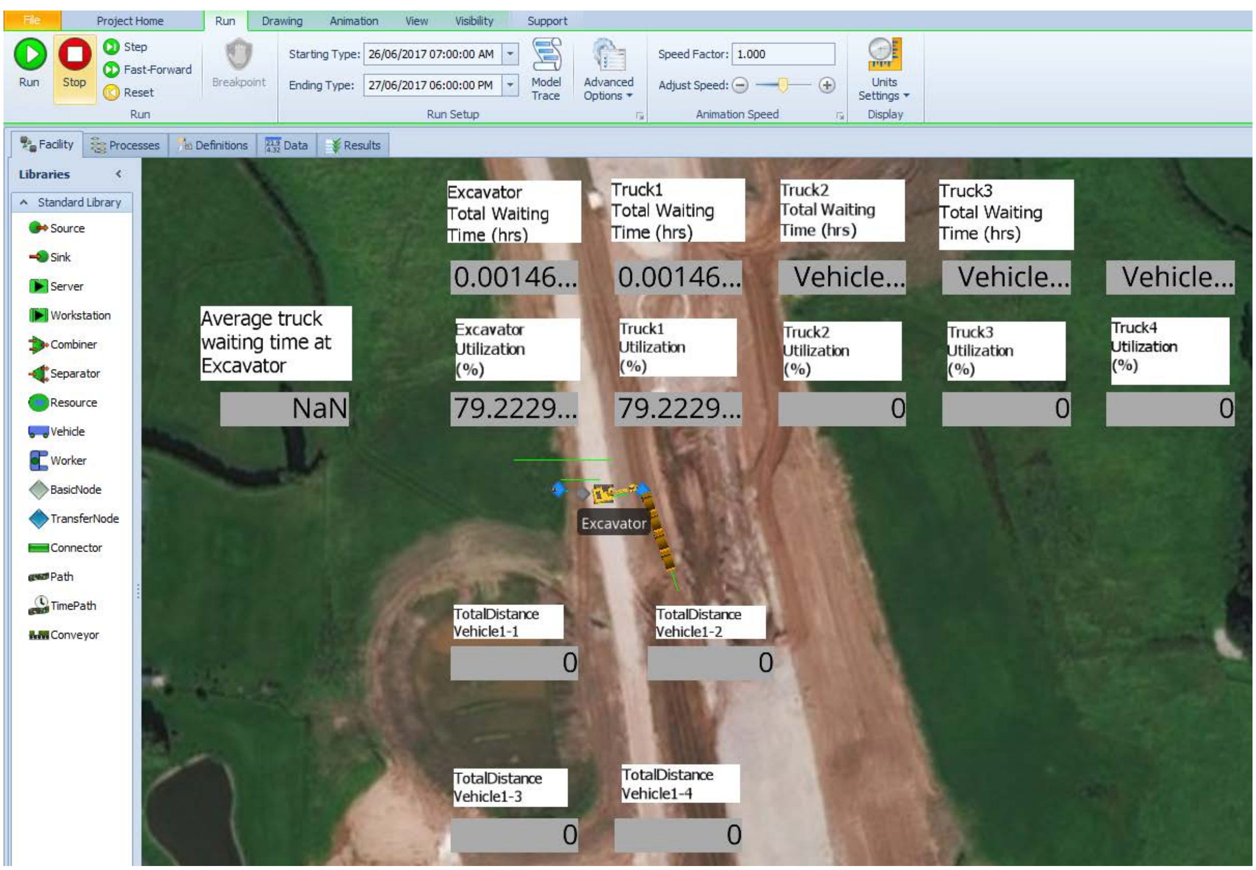


Figure 5.17 On-screen results display function which makes it easier to monitor the behaviour of system after any change

Its development and operation have been illustrated step by step in detail which will assist people using the combination. It is also harmonious with the recent technologies used by the majority of organisations as most of the construction-related software packages have built-in simulation modules as well. Companies can use the model created in this case study without the need to buy any particular software which will further save capital. Since there is no mention of a specific organisation or their data etc., so there are no ethicality concerns, and it can be replicated without hesitation. The only side effect it has is that the person running this software needs to have some fundamental knowledge about simulation techniques and how they work, which is not complicated and there are various free resources on the internet to obtain it.

Figure 5.17 above shows the strong feature of on-screen results display which was used to determine the utilisations of excavator and dump trucks in real time. If the sink (Dumping point of the earth) was moved or the speeds of vehicles were changed while the model was running, it affected the utilisations instantly and was noticed using these ribbons. After an experiment was finished, they also displayed final results which were used in different scenario testing. These ribbons were for measuring total distance covered by dump trucks, excavator utilisation, trucks utilisation (for each truck out of 4), trucks waiting time and excavator's idle time.

1.6.1.3 <u>Structure</u>

Structure of an artefact can be assessed by its simplicity, style, level of detail, completeness, consistency and homomorphism. The artefact, the simulation model and its guidelines are pretty simple regarding its development and practice. Difficult technical expressions are avoided as much as possible to enhance its simplicity and thus the applicability. A person with basic knowledge of IT and simulation can follow the procedures outlined in section 5.4 and achieve their desired goals. The method of development and the model is quite generic and is widely used globally. The software used for its formulation is readily available for free as well as paid options for businesses exist. However, a free (demo) version can also run the developed model due to its advanced yet straightforward style. While the artefact is understandable and straightforward, however, its level of specification is exceptionally high. The data required for the creation of such a model may take months to gather and then further time is needed for its development, rigorous testing and refinement.

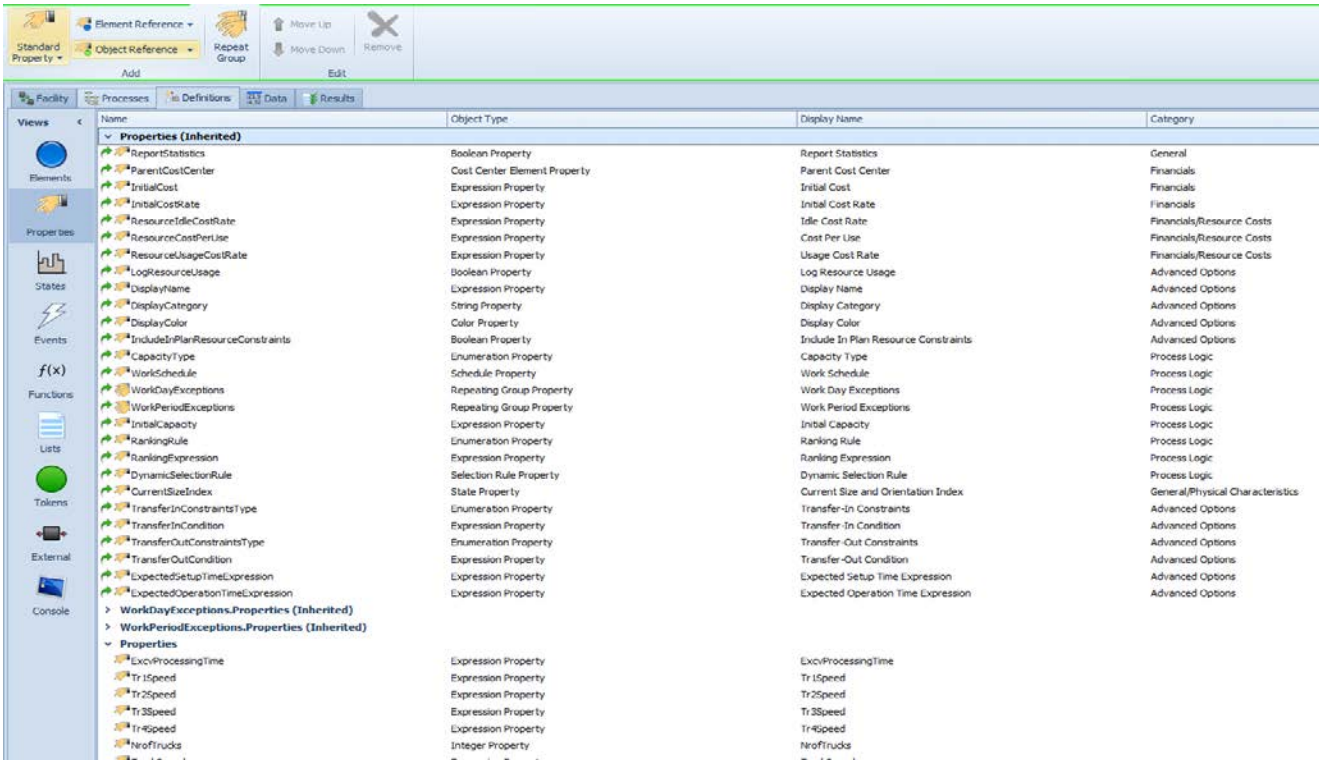


Figure 5.18 Properties tab of a simulation model showing the level of detail it can handle and require for a fully functional simulation model.

Figure 5.18 above displays the properties tab in Simio where different resources are listed, and their properties are listed. Some of these characteristics are picked by default whereas most of them have to be defined or imported like the size of the machine, running speed, breakdown frequency, any events attached to it etc. The events tab is a powerful feature which can program the behaviour of the model if an event is linked to it. In earthworks case study, an event was created to move the excavator 1 meter after a certain amount of soil was dug and removed.

The structure of the artefact is the most essential and critical part of it. If the structure is weak and not adaptable, it will fail and will not be applied practically. In simulation modelling and construction works, scheduling is an important element for the successful delivery of the project. This simulation model used the scheduling practised by the contractor and was imported using the excel format. Figure 5.19 below shows the work schedule tab in simulation software which was customisable from hours to weeks and months etc. for different types of resources like operators, drivers, dump trucks, excavators and other helping crew.

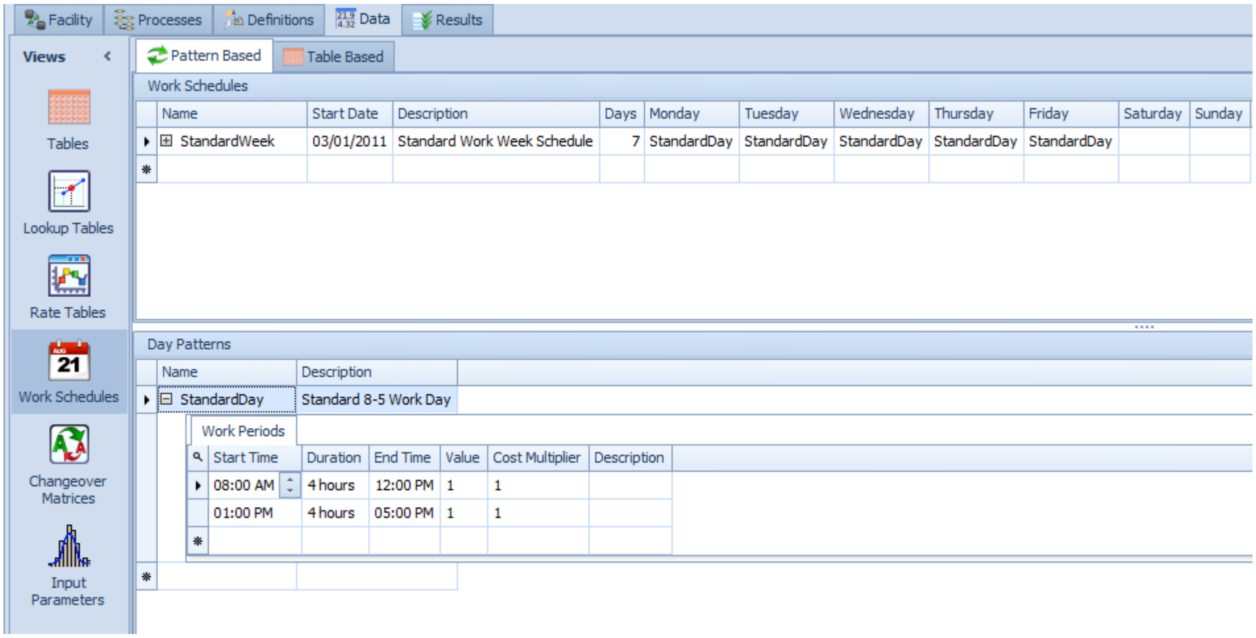


Figure 5.19 Work schedules input in Simio that can be linked to various sub-contractors using excel.

Discrete Event Simulation as described in section 2.3 in detail requires the highest level of data/specifications/information to work accurately compared to the other two modes of simulation, i.e. agent-based and system dynamics. The model along with its comprehensive description and guidelines makes it complete and consonant. A complete artefact explains in detail about how and why it was produced, its validation and instructions/guidelines for practice. Lastly, homomorphism means its correspondence with other models and fidelity to modelled phenomena.

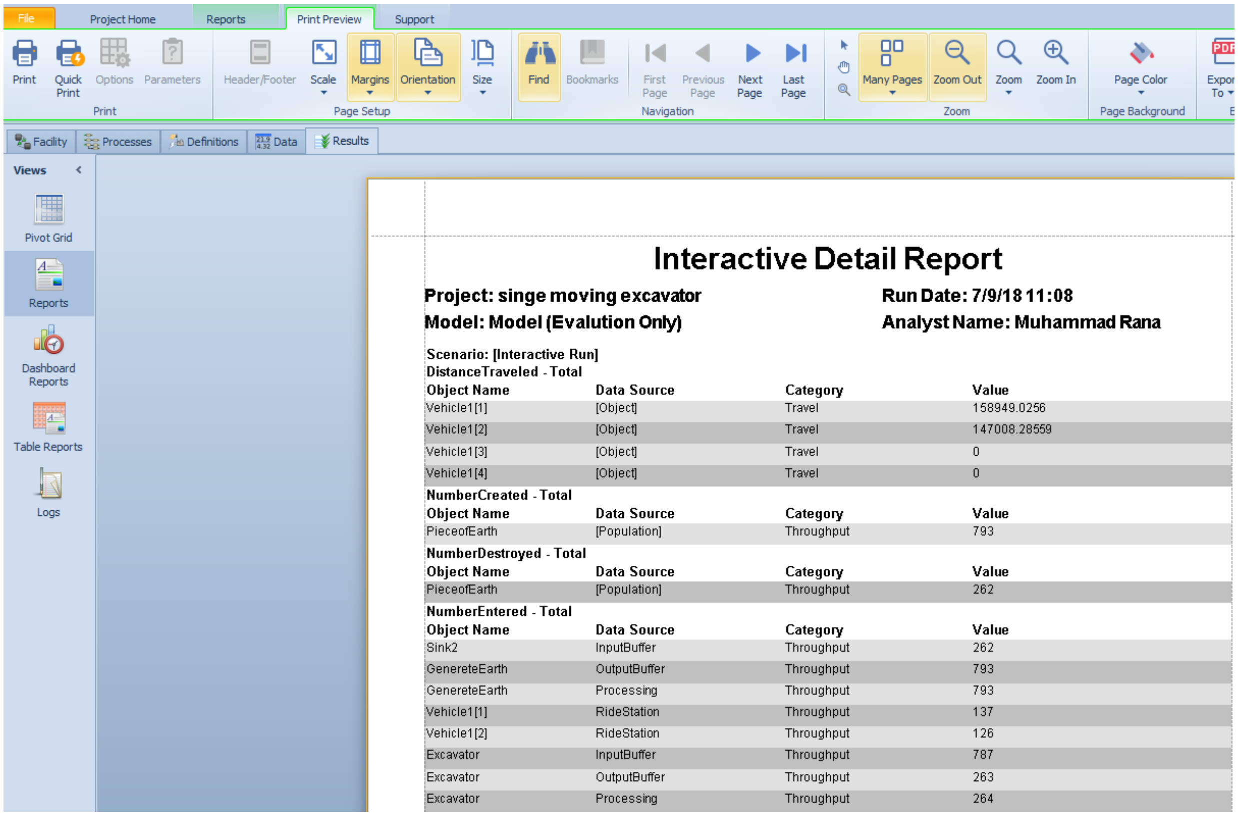
The simulation model developed in this case study corresponds adequately with other simulation models, e.g. currently, it only deals with the operation stage of Earthwork machines that are drilling and moving soil; however, it can also be associated to other models concerning the delivery of materials and possible delays as well as risk reduction models. Regarding fidelity to the modelled phenomenon, this model has impressive 3D graphics which mimics the original process very well making it easy to understand for technical as well as non-technical people as shown in Figure 5.20 below. The level of detail used and the focus groups with experts evaluated its exactness and precision.

Figure 5.20 3D detailed graphics of Earthworks case study in a computer-based environment.

5.6.1.4 Activity

Activity dimension is characterised by the accuracy, performance, efficiency, completeness and consistency of a developed artefact. The developed artefact is accurate, exact and precise due to its maximum level of detail. Its performance has been experimented and validated theoretically as well as with experts in simulation and construction processes in the United Kingdom. During the focus group workshop, the model was explained and demonstrated in detail, and the experts also ran various experiments to examine its performance and capableness.

Its efficiency is also evident from the fact that it does not require some specific machines to run or specialised knowledge about simulation yet works well to improve any as-is resurfacing process regardless of the structure of road, traffic or other varying conditions. Figure 5.21 below shows the results of simulation software that has the ability to develop reports, pivot grids and charts based on the parameters defined in the beginning. It will automatically include the utilisations, idle times, breakdown periods and bottlenecks etc. for all the resources involved. Unnecessary items can be turned off by using the filter option.



Interactive Detail Report

Project: singe moving excavator **Run Date: 7/9/18 11:08**

Model: Model (Evalution Only) **Analyst Name: Muhammad Rana**

Scenario: [Interactive Run]

DistanceTraveled - Total

Object Name	Data Source	Category	Value
Vehicle1[1]	[Object]	Travel	158949.0256
Vehicle1[2]	[Object]	Travel	147008.28559
Vehicle1[3]	[Object]	Travel	0
Vehicle1[4]	[Object]	Travel	0

NumberCreated - Total

Object Name	Data Source	Category	Value
PieceofEarth	[Population]	Throughput	793

NumberDestroyed - Total

Object Name	Data Source	Category	Value
PieceofEarth	[Population]	Throughput	262

NumberEntered - Total

Object Name	Data Source	Category	Value
Sink2	InputBuffer	Throughput	262
GenereteEarth	OutputBuffer	Throughput	793
GenereteEarth	Processing	Throughput	793
Vehicle1[1]	RideStation	Throughput	137
Vehicle1[2]	RideStation	Throughput	126
Excavator	InputBuffer	Throughput	787
Excavator	OutputBuffer	Throughput	263
Excavator	Processing	Throughput	264

Figure 5.21 Reports tab in simulation software that can develop reports based on the experiments performed.

Figure 5.22 on the next page demonstrates the results in pivot grid format where all the statistics are displayed by default at the end of a shift or a particularly designed experiment. Statistics, which are not required, can be turned off by simply selecting them and clicking the on/off button. The consistency and completeness of an artefact can be assessed from its ability to work with other models, adapt to changes promptly, functionality remains similar in any scenario etc. All these factors have been applied to the developed simulation model and its guidelines, and it has passed all the tests.

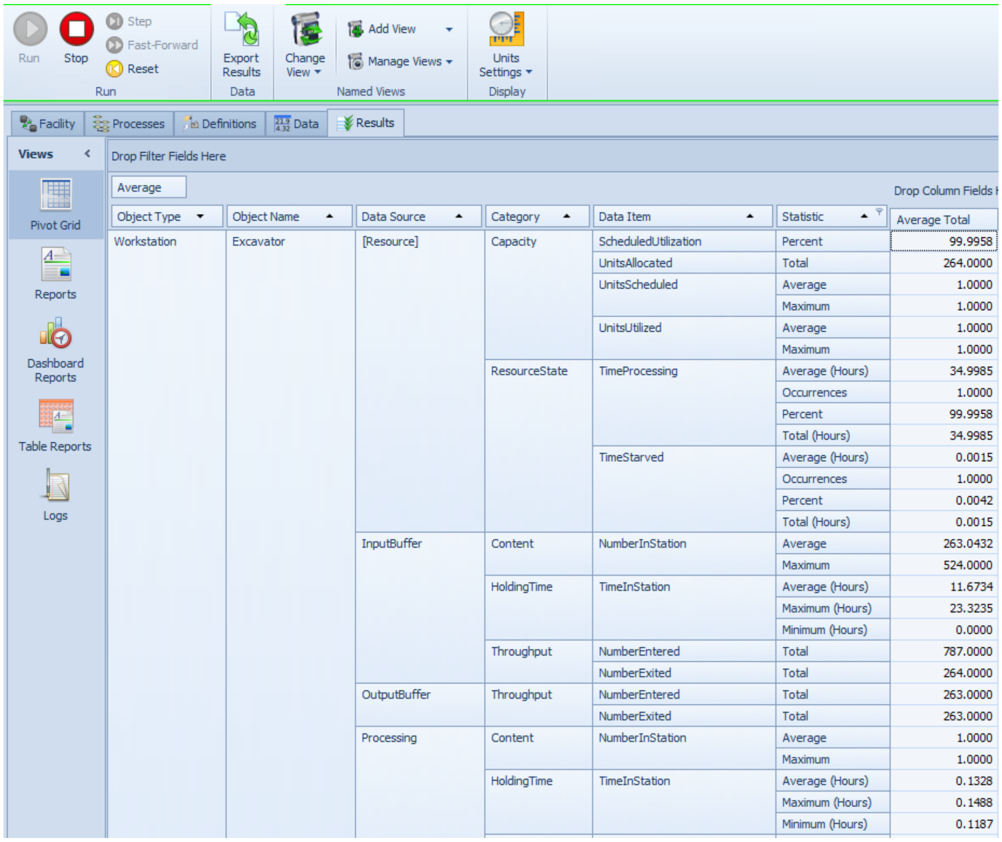


Figure 5.22 Results tab for 2nd case study showing various vital numbers like Utilisation, idle time and breakdown etc.

5.6.1.5 Evolution

Evolution is the robustness and learning capability of an artefact. As mentioned in above points, Earthworks simulation model was tested under various changing conditions by the developer and the assessors, and it demonstrated success in withstanding adverse conditions and harsh testing. Its learning capability is literally unlimited because this developed model only deals with operation stage of Digging soil and transporting it, however, it can be populated with more details or can be linked to other models regarding risk assessments, effects of severe weather, decision process modelling, resource management and other information can be added as well. Figure 5.23 below shows the scheduling and configuration tab of Simio where different schedules from sub-contractors can be linked simply using their databases or from a combined excel file.

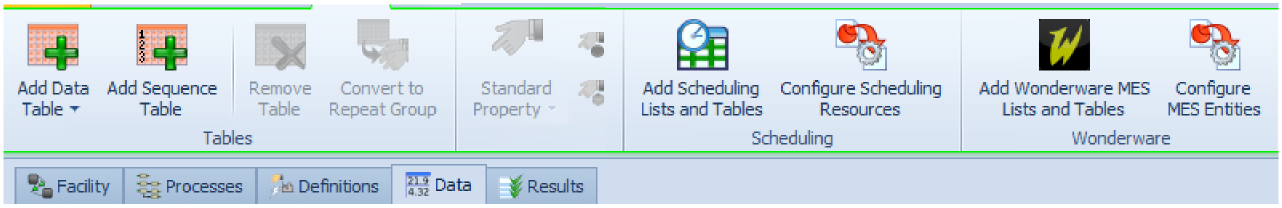


Figure 5.23 Top ribbon of software showing its abilities to add data from external sources add scheduling and timetables for the simulation shift and link to wonder ware.

Figure 5.24 below demonstrates the experiment tab of Simio which is the backbone of the discrete event simulation modelling and this case study. Here, users can define various scenarios while changing the speeds, distances, types of machines, their numbers and other resources etc. The system will automatically assume these setting and will run the simulations for a given number. The process can be fast forwarded and depending on the speed of computers; it should not take very long. In this particular case, hundreds of runs were made for 6 scenarios under an hour.

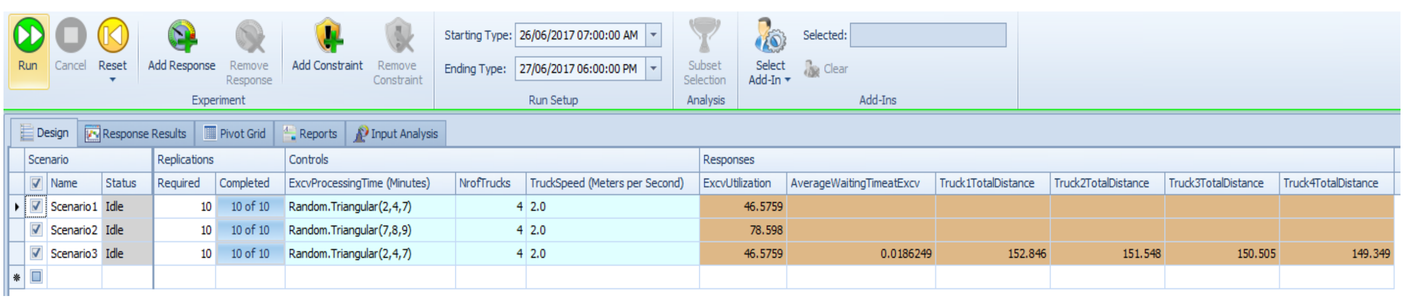


Figure 5.24 Experimentation tab of Simio which is one of the most critical features of this software to experiment different what-if scenarios.

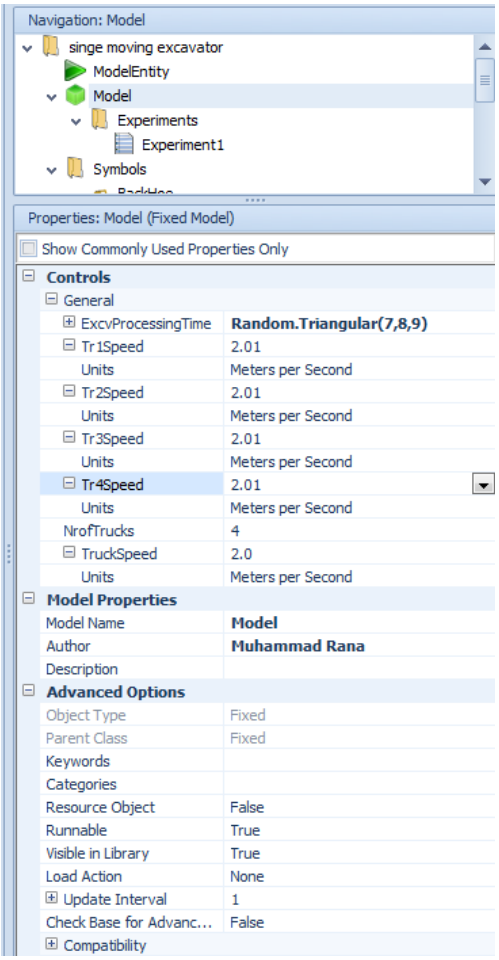


Figure 5.25 Modifiable properties of vehicles and other resources.

Figure 5.25 above shows the properties tab which can be seen after selecting an object like a person or a vehicle or a machine. Then its properties like speed, processing time, type of work, idle position, start and end time etc. can be defined. This shows the level of details that goes for each object and at the same time demonstrates the adaptability of this simulation model which can be modified to different similar conditions by simply changing these numbers. This makes it more applicable for various earthworks operations of a similar nature in different countries.

5.6.2 Validation from a focus group of experts.

The validation of these scenarios, their feasibility and applicability were done through a focus group in a small workshop held at the University of Salford. Highways departments in the UK have different Tier1, 2 and Tier 3 contractors responsible for managing the road networks as well as constructing and maintenance works. One expert from each Tier was available and chosen, and the simulation model was run in front of them to demonstrate its working and all available functions. It also presented them the data that was used, how it was collected and why different scenarios were chosen. Positive feedback was recorded from the experts especially for the detailed analysis about the effect of haul lengths and effects of vehicle speeds which are otherwise hard to investigate.

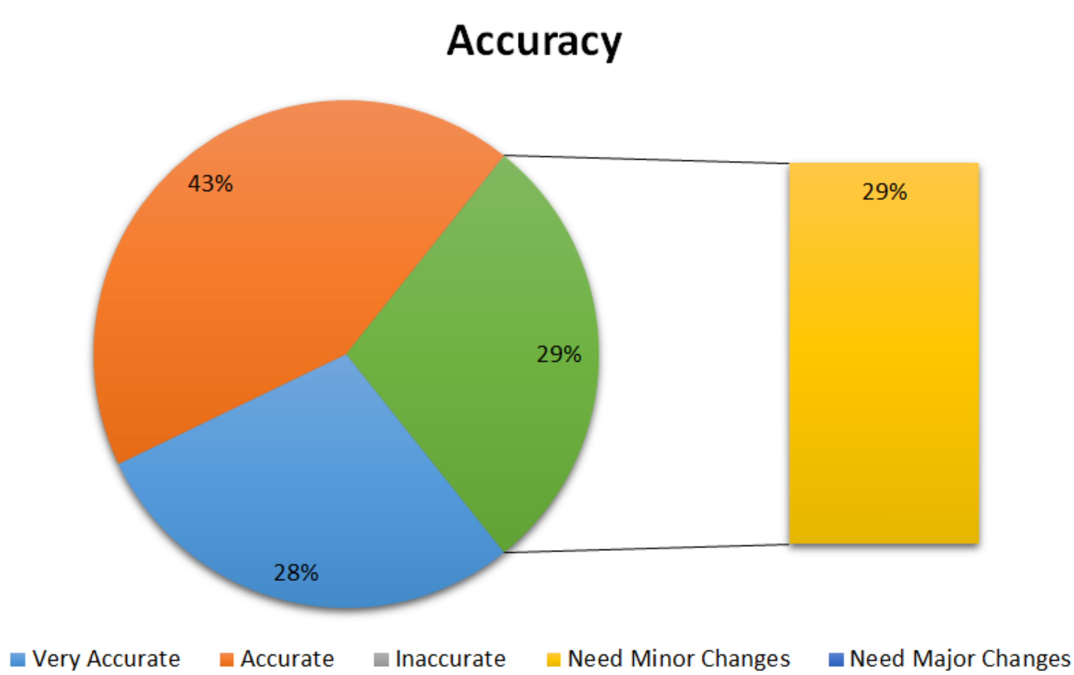


Figure 5.26 Responses of focus group attendees about the Accuracy of the Artefact (Earthworks optimisation).

After developing an artefact, verifying and validating it is the most important task. If a solution has been developed that his not applicable in real-life, it will have no value for the industry or the users that it was designed for. For this purpose, this artefact (simulation model of

Earthworks) was validated theoretically and through a focus group. Figure 78 above shows the responses of focus group participants about the accuracy of the model. 28% of the participants strongly agreed that the model is accurate. Overall, 43% agreed that it does not a lot of changes or modification, and 29% said that minor changes were required. If these changes are performed, then this model can be utilised in similar earthwork scenarios in the UK and other countries too as this operation is quite similar everywhere.

After validating the accuracy of the model, its strengths were questioned about from the experts. For the researcher, it might be efficient for reasons that carry no value for the industry and vice versa. Figure 5.27 below shows the response of their answers about the efficacy. 33% of the experts mentioned that the ability to analyse in this simulation model is the strongest part, whereas 27% of participants were impressed with the as-is situation capturing. They mentioned that only DES has the power to mimic the actual situation in the computer-based environment. 3D graphics work and data collection techniques scored 20% each. Discrete event simulation has powerful graphics which also makes it easier to understand a complex process with multiple operations inside it.

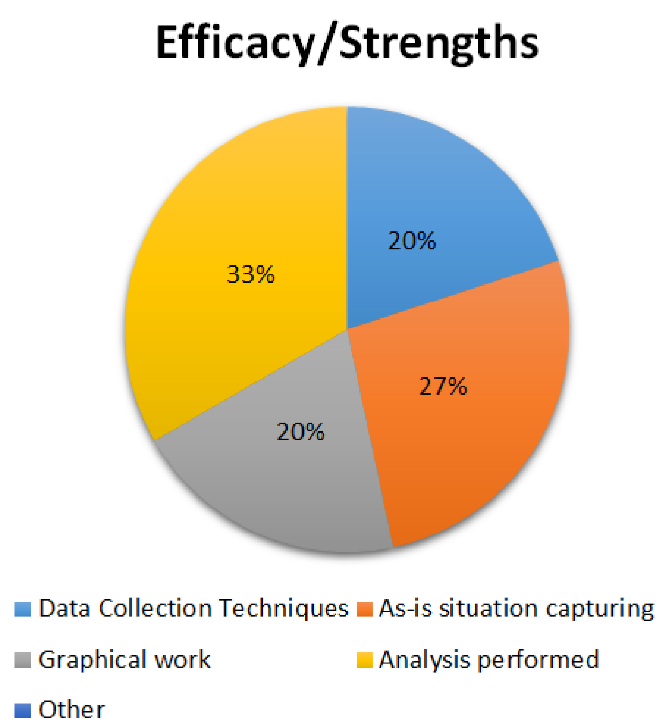


Figure 5.27 Focus group's responses about the Efficacy or Strengths of the Earthworks Optimisation Model.

The principal focus of this investigation was to develop simulation models that can are non-exclusive in nature and can be applied to other, similar projects around the world. Many people think that simulation modelling is an expensive and complicated task. However, they can efficiently use this model with the free version of the software used in this case to study their as-is process in detail, experiment different scenarios as needed according to the situation and improve the utilisation of their human and non-human resources. Figure 5.28 below shows the responses of participants about the practicality of the artefact.

During the technical evaluation, the practicality of the artefact was discussed numerous times. 72% of the experts, after looking at the working model of earthworks, believed that the model is practical and can be applied to other, similar projects in nature. 14% thought that some minor changes might be required like the addition of vehicles break down, realistic time for refuelling and the effect of break times etc. Remaining 14% said that it could be further improved after using it once on a different live project to get rid of any non-realistic assumptions.

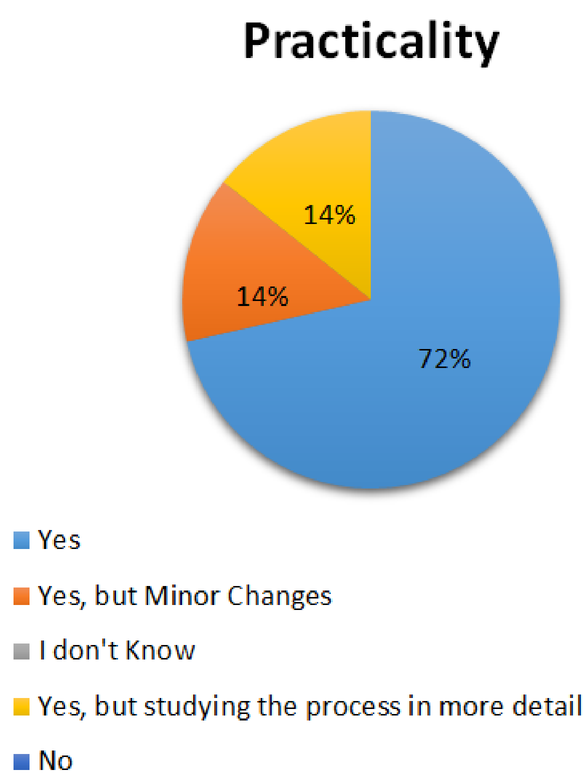


Figure 5.28 Feedback of focus group regarding the Practicality of the artefact.

28% of participant response of participants about the changes which will improve the artefact. 50% of the experts stated that the analysis performed can be further enhanced by combining it with other simulation models like risk assessment, live weather data, live traffic data and using actual project plans in the software. This task can be easily done and has been explained in detail in section 5.6.1.5 Evolution. However, it was out of the scope of this research work as it was designed to improve the current state of the work by reducing waste of resources and increasing their utilisation using lean and simulation techniques.

If the research delved into the risk management and project planning aspects, it would have required more time, and the artefact would not have remained Generic in nature. It would become more project specific and would kill the basic purpose of this research work. 20% of the participants agreed that the graphics are very clear and easy to understand, however, if the interaction of machines can be linked to humans, many health and safety issues can be solved using this model. 20% mentioned the data extraction procedure and 10% participants had other minor changes to suggest that were recorded and implemented back in the model.

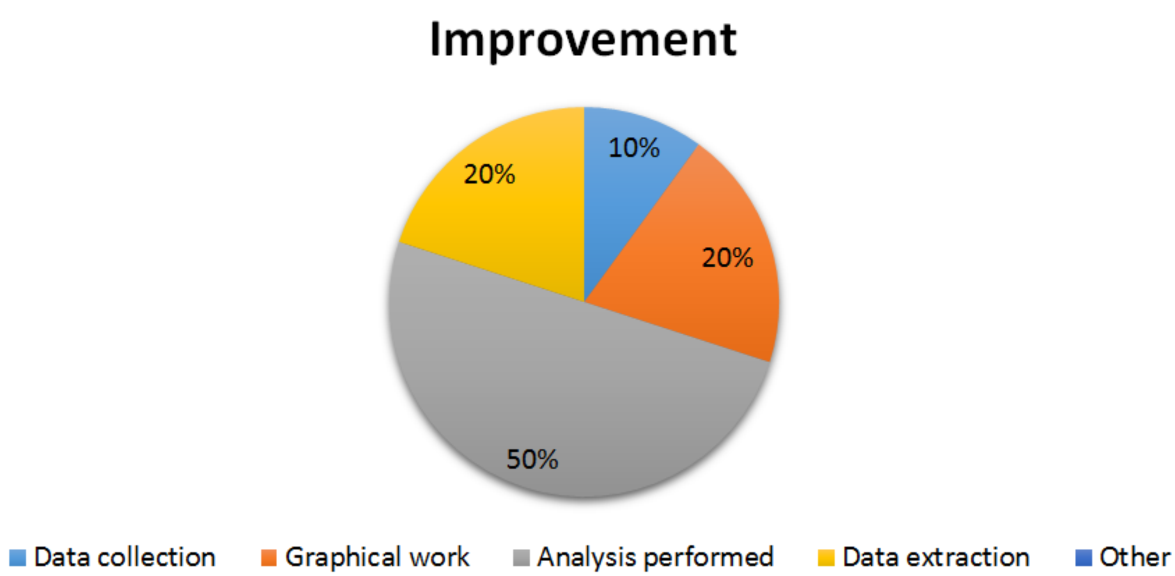


Figure 5.29 Focus group's responses regarding the areas where improvement is required in the model.

Cutting and filling is a conventional operation which is profoundly affected by the weather and the changing length of cut and fill points. This experiment sheds light on both the factors and investigated their impact on the efficiency of the overall process and the utilization of excavator and trucks. This experiment will lead to recommendations and suggestions to an industry that will be based on their demand and built using real-life data.

During the focus group workshop, the most important session was to record the feedback of the participants after demonstrating the model to them. This reliability testing would decide if the artefact is mature enough to be published or require further changes, and if so, what sort of changes are required and what are the strengths of the model. Figure 5.30 on the next page shows the results of reliability analysis where the majority of the participants agreed that the discrete event simulation had been applied at the right stage of the process, i.e. execution stage of the project as most of the resources are deployed during this stage. They also approved the data collection process after the researcher explained to them the whole process of the data collection about this particular case study.

Since most of these scenarios were suggested by the industry partners, in the beginning, there were fewer questions about why these scenarios experimented, and more questions were asked about the data analysis and how it helped with it. Due to this reason, the assumptions made by the researcher during the development of the simulation model were also approved by the experts. It is a natural process to assume various things during simulation model development to reduce the complexity of a model. If these assumptions are non-realistic, they will reduce the practicality of the artefact and will make it unusable.

Majority of the focus group participants believed that other manual approaches or mathematical tools could not replicate the same work due to their incapability to simulate a complicated process, perform various what-if scenarios and visualise it using real life scale and graphics. During the previous questions it was asked that if the current model required some changes and the experts suggested some minor changes, however, when they were enquired if it needed significant changes, they disagreed as shown in the last spike in the Figure 5.30 shows. If the researcher was not collaborating with the industry participants and if these scenarios, analysis were not suggested by them, it would have attracted a lot of criticism.

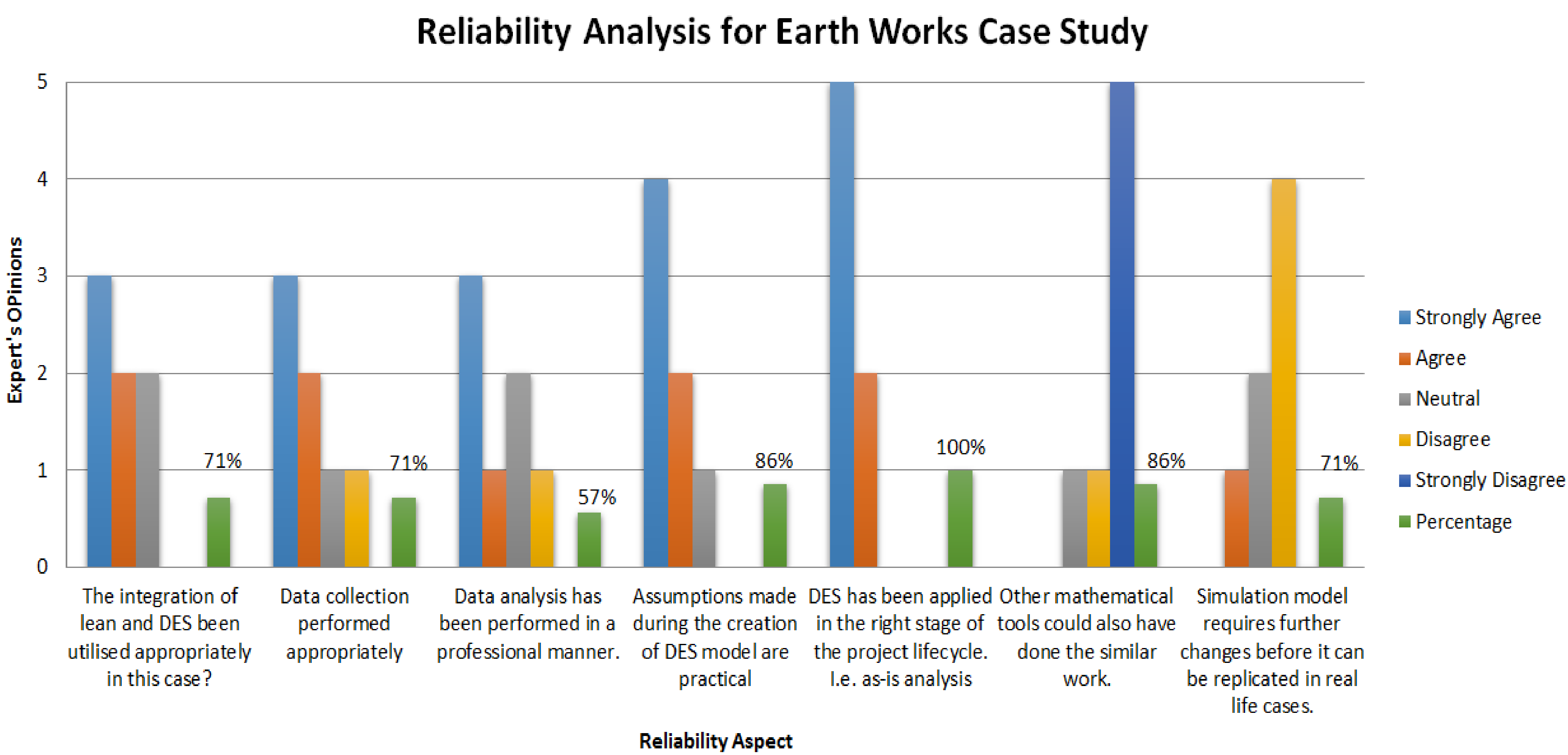


Figure 5.30 Reliability analysis of the Earthworks case study after the focus group.

5.7 Discussion

A significant amount of work has been done before to improve the earthworks operations. However, it has been focussing on various stages of earthworks. One of the difficulties usually seen is that each site requires its own model to be created and then the simulation trials can be run. It can be challenging and time-consuming and repeating the same thing over and over. This simulation model set up in this research has no fixed route, the number of vehicles or speeds etc. Everything has been defined as a variable rather than a fixed entity. The advantage is that it can be used again on a slightly different work site by merely modifying the number of vehicles and the distance between the excavation and dumping point. Therefore, it is necessary to share this simulation model with other stakeholders or to open-access on the internet etc. so that more people can benefit from it.

Most of the scenarios experimented in this case study were suggested by the industry partners who wanted to study the process in the computer-based environment and perform various tests without disturbing the on-site operations. Cut and fill operation is a prevalent process around the world due to ever-increasing construction demands. It can be enhanced by understanding the factors that hinder its performance and modifying the number of machines as the length of the filling point changes. Such an interactive arrangement can only be designed in the simulation environment, and it should be utilised to its maximum potential.

Scenario 3 suggested that using bigger trucks (where possible) can also enhance the utilization of excavators. However, the availability of bigger trucks (80 tons) and the site location will decide its final implementation. Scenario number 4 was most stable with 2 excavators loading two trucks each. This showed almost 71% efficiency for excavator that is practical to achieve and the extra excavator can be justified as well for its benefits. Scenario 5 also had two excavators with 3 trucks each; however, this combination fully utilized the excavators up to 99% which is only possible in theory. However, in ideal circumstances (no breakdown or lengthy refuelling), it’s a very productive arrangement.

Chapter 6 : Discussion, Conclusion and Future Recommendations

Sections

6.1	6.2	6.3	6.4	6.5
Introduction	Discussion	Conclusion	Recommendations	Summary

6.1 Introduction

The fundamental aim of this research was to demonstrate how the integration of simulation and lean can improve construction processes at the operation level to a great extent. To achieve this aim, about five objectives were identified. This chapter individually discusses all these objectives one by one regarding if they were met and how and the lessons learnt during the process. The individual and detailed discussion have been performed in each case study that included the knowledge acquisition, formalisation, model development, testing and validation stages in in-depth detail. The discussion sections also described different what-if scenarios that were planned and tested in both case studies and then concluded with the most efficient ones.

This was scientific research which started with detailed literature review about the productivity challenges in construction and possible solutions and then looked into simulation techniques and finally applied this combination on two different case studies to achieve the aim. This chapter also concludes the thesis and finally present a set of recommendations for future work.

6.2 Discussion

6.2.1 Objective 1

The first aim was to generate an understanding of productivity challenges in highways/construction sector in the United Kingdom. The initial literature review indicated that construction has been lagging behind if compared to manufacturing, processing or even healthcare sectors. What is even more alarming that UK's construction sector has been performing worse than many other developed countries. Road sector, in particular, has been suffering as well due to low productivity, conflicts with contractors, lack of funds, late delivery, and outdated maintenance techniques. One of the primary reasons is the resistance to change. It can be a change in working attitude, timings of work, methods and adoption of new technology.

Road space is becoming a scarce resource due to an ever-increasing number of private users. A study by INRIX and CBR (2014) estimated that between 2013 and 2030, the United Kingdom would pay the total accumulative cost of more than £300 Billion caused by congestion. This is equivalent to 18% of the UK's Gross Domestic Product (GDP) in 2013. This shows the ever-increasing demand for traffic management and roads up gradation. Maintenance of current roads and constructing new roads never stops around the world. As the traffic increases, existing roads need expansion and up gradation. Due to large volumes of vehicles and frequent travels, existing roads lose their strength, aesthetic appearance, skid resistance and ride quality and require preservation and maintenance (Burningham and Stankevich, 2005).

Similar observations came from annual (UKIPR, 2015) showing that the majority of construction projects were completed behind schedule in the UK. Furthermore, a survey by the Construction Management Association of America (CMAA, 2005) showed that 40-50% of all construction projects failed to meet their time and cost targets in a developed country like the USA. This happened while the federal government implemented various productivity improvements in areas like planning, design, cost control, quality control, craft training, scheduling, safety and information technology (Picard, 2004).

This objective was successfully achieved by reviewing the appropriate literature about construction productivity challenges in the UK. It is the first objective and will pave the way for the following tasks; therefore it was critical to capture the right data in this step. During the literature review and collaboration with industry partners, it became clear that the construction sector in the UK has been underperforming as compared to manufacturing or healthcare. Several factors need to be addressed in this area to increase the efficiency. Some of them are poor communication, poor organisation, contractual misunderstandings, weak short-termed planning, missed connections, limited talent management, flawed performance management and insufficient risk management (Green, 2016). If these issues are dealt with in a professional manner, straitened circumstances can be mitigated easily. However, the scope of this research is limited, and it can only look at a particular aspect of the process. Therefore the author focussed only on the operation levels of two projects. It was realised during the literature review, industry interaction and personal experience that Operation level work is usually the least productive and consume majority of resources.

6.2.2 Objective 2

The second objective of this research was to evaluate the need for computer-based techniques in construction and specifically highways operations. Simulation is the reflection or imitation of a real-world operation or a system (Banks *et al.*, 2010). Simulation modelling is one of the many modern techniques to solve real-world problems by creating a context within which the situation can be investigated (Law & Kelton, 2000). In various everyday situations, it is not feasible to experiment with real objects by building them from scratch, destroying them or making changes (Borshchev, 2014).

The objective was achieved by thoroughly reviewing the contemporary published literature about the use of Discrete Event Simulation in the construction and highways sector specifically. It demonstrated that the simulation methodology had been profoundly implemented in the manufacturing, healthcare and processing industries. However, the construction sector did not fully utilise this computer-based process optimisation method, and even if it did, it was extremely limited in the highways sector. The interaction with industry partners from various companies also strengthened these findings that more can be achieved by using a combination of lean and simulation tools.

Simulation modelling has been used in construction processes and is regarded as a reliable tool in project management (Gowda, Singh and Connolly, 1998). Engineers in a construction company can model any system or a process of any size to gain in-depth knowledge of the process and make it more efficient. Simulation modelling provides the operation planner with a medium for modelling real life and real-time processes and then running various what-if experiments in a computer-based environment. The implementation of simulation techniques in highways context is limited, and only a handful of studies have been done to advance the process, e.g. by (Maji & Jha, 2009; M Marzouk et al., 2011; Jones 2011). Existing optimisation approaches rely heavily on manual process methods like Process Activity Mapping, Quality Filter Mapping, Decision Point Analysis and Value Stream Mapping, etc. which have many limitations.

The implications of this research were twofold. First, it studied, observed and simulated the as-is highways processes to improve it. Secondly, it encompassed many relevant stakeholders at validation stages to verify and validate the proposed results and gain consensus amongst them. Stakeholders that can benefit from this research are transported departments, highways agencies, resurfacing companies, highways maintenance contractors and finally the general motorists.

It was demonstrated in this objective that simulation models can provide enough information to expedite and verify the decisions of executing lean manufacturing techniques. It has also assisted organisations during the implementation stage to achieve the aspired results (Abdulmalek and Rajgopal, 2007).

6.2.3 Objective 3

The third objective of this research was to explore the synergy between lean and computer-based process optimisation methodologies and integrate them for enhanced benefits. The combination of lean and simulation techniques can lead to an improved corporate image, better process flow, increased compliance with customer's expectations and enhanced employee utilisation, mortality and commitment. It can also reduce the unnecessary material usage, energy consumption, cost and lead time, and water usage etc. The overall results would be improved productivity as a whole that will also impact health and safety aspects positively. Different people have been working on the mixture of both optimisation techniques and have termed it as a win-win situation. Simulation techniques and lean principles together render the ability to rehearse and experiment with various process improvement scenarios then pinpoint the options which are most effective concerning waste, resource utilisation and overall effectiveness (Uriarte *et al.*, 2016). It can also manifest accurately how a process will behave before and after executing a lean manufacturing technique which means correct lean implementation at the first attempt (El-Haik and Al-Aomar, 2006; AbouRizk *et al.*, 2011).

It was performed and shown in both the case studies presented in this research work. In the first case study, the lean aspect was borrowed from Andrew Moore's work performed for the Highways Client and his improved/enhanced scenarios were used as an example in the simulation model. In the second case study, earthworks, the lean aspect was performed by the researcher himself by cutting waste present in the process like break times, late start, reducing vehicles break down and using the correct configuration of earth moving vehicles. In both cases, after improving the base processes concerning productivity, the simulation model was created for both operations which further enhanced their output and efficiency. It also demonstrated that the deficiencies in the lean methodology can be overcome by using simulation methods and that lean concepts can be more readily understood using simulation techniques (B J Schroer, 2004). It helps in the implementation of lean tools and can assist in deciding the application of lean manufacturing floor layouts, which is a significant decision (Detty and Yingling, 2000b).

A lean approach to construction or a manufacturing process can have a meaningful, positive impact on efficiency, productivity and profit. Lean manufacturing is a methodical process to eliminate waste within a manufacturing or a construction process (Hines and Rich, 1997). Lean reflects waste produced as a result of unevenness in workloads and the overburdens, i.e. inefficient resource utilisation. It is viewed from a client's perspective who may also be the end user of the service or product. For them, "value" is any process or action which a customer would be happy to pay for (Singh and Sharma, 2009).

Simulation gives manufacturers the ability to present a powerful and animated display of various processes in a very dynamic way to highlight restraints in any system which stimulates the need for change at operational or managerial level (Robinson, 2005; Abdulmalek and Rajgopal, 2007). Whether your simulation is showing a large queue building-up or a series of activities grinding to a halt due to a lack of stock, nothing is more effective at communicating these types of issues than letting staff see this happening for them.

6.2.4 Objective 4

The fourth objective of the research was to undertake pilot projects involving simulation techniques in some of the real-life highways projects. For this purpose, two case studies were chosen due to their availability and rich accessibility to data around them. The first case study was about resurfacing, which is a road maintenance procedure frequently carried all over the world and is one of the most significant highways operations. The second case study was about earthworks which involve digging and movement of earth from one place to another. Although both these processes are different from each other, they are both very critical to highways construction and maintenance and are highly inefficient in terms of productivity and resource utilisation.

The first case study of resurfacing was also called “1000 ton trial”. It was a joint venture performed by the highways agency, resourcing and other contractors’ responsible for white lining and traffic management (Moore *et al.*, 2015). The motivation was to maximise the production each night and achieve maximum results. They managed to reach high results and productivity was also increased using traditional lean approaches (Qasim, Aziz and Alfar, 2017). The data was stored with Highways England and was obtained from them by the researcher for research purpose and to improve it even further.

New infrastructure and congestion relief projects can be delayed and are usually delayed due to various reasons, mainly financial problems. However, maintenance (resurfacing, rehabilitation, etc.) projects cannot be postponed as they directly affect the road network. As soon as a road is built, it starts deteriorating due to many causes like weather, traffic and quality of materials (Department for Transport, 2013). UK Government has announced a £1 billion budget per year for maintenance projects throughout the network (Department for Transport, 2015). Though, the most significant demand is to improve the maintenance projects to utilise the money in the most efficient manner and deliver quality. Construction productivity has been on a decline for decades and maintenance activities had the same performance (UKIPR, 2015).

The second case study was regarding earthworks optimisation. It is a complex task to schedule the earthworks involved in various projects. Different alternative scenarios in worksite layout and using various machine configurations have to be dimensioned and evaluated reliably. Any wrong decision taken at this stage will lead to uneconomic situations and delays leading to increased cost and project duration (Aziz, Qasim and Wajdi, 2017). Hence, it is vital to improve earthworks operations from initial stages till the end. The planning stage of earthworks can be improved using discrete event simulation techniques. It can be done by measuring the performance of earthmoving machines and then strive to increase the performance using various scenarios. According to Wimmer et al. (2012), a simulation tool can also be combined with a mathematical optimisation model to minimise the transportation cost by reducing haul times.

Earthworks involve very few activities, personnel and equipment but consume a comparatively significant percentage of the construction budget. Earthworks deal with soil and digging which makes it critical to control the environment as well as production (time, cost and quality) issues. Various lean studies have been performed in the past to increase the performance of production and environment in construction (Belayutham, 2015).

This objective was successfully achieved as the above-described case studies were selected, investigated, simulated and eventually improved as well. The findings of the first case study were also published in a Q2 journal and two peer-reviewed conferences where it also managed to win Best Paper of the Conference Award.

6.2.5 Objective 5

The fifth objective was to validate the findings of the case studies through industry experts. Typically, in similar scenarios, validation of artefact is done by functional and structural testing (Hevner *et al.*, 2004). The artefact, in this case, is a simulation model which requires even more robust experimentation, and the reasons behind its development have to be explained thoroughly. Therefore, the third type of validation has also been used in this research work, i.e. Theoretical validation using a hybrid model developed by (Prat *et al.,* 2014)

Hence, the validation was performed in three sequential stages, theoretical validation, and functional testing. Theoretical validation is a rigorous method that questions and challenges all the different aspects and dimensions of a product or artefact to ensure it is of appropriate quality. Its dimensions are to evaluate the goal, environment, structure and the activity of an artefact. Evaluation criteria details include efficiency, validity, generality, consistency, completeness, simplicity, clarity, style, homomorphism, level of detail, accuracy, performance, efficiency, robustness and the learning capability (Hevner *et al.*, 2004; Venable, 2006; Hevner and Chatterjee, 2010). Once an artefact has passed all these questions, it can be considered as a valid product which has all the characteristics described above.

During the structural and functional testing, the simulation model or the prototype is tested using first the original datasets and then artificial datasets to prove its efficacy, reliability and accuracy. Tens of simulations can be run to obtain satisfactory results and investigate whether it fulfils the requirements and restraints of the problem which it was meant to solve. The authors usually do take a back-up of simulation models during the development stage which is not very different from each other. These models can be matched against each other to see if they solved a specific issue and how.

For focus group, eight experts were recruited (based on their experience and knowledge) to carry out the usability test of the artefact. The users, who were the experts in simulation modelling, lean and process optimisation, were briefed about the challenges in productivity at the operation level and how this artefact contributed to solving the issue. Various simulation models have been developed and utilised in the past to enhance decision making, risk management, logistics and delivery of materials etc. However, this model has focussed on the operational level about what happens on the worksite and how it can be improved. The experts were also guided through the development of both simulation models, how they were created, how the data was collected, how testing was performed and finally how the results were verified against the theoretical model.

6.3 Conclusion

The aim of the research has been achieved by developing lean integrated discrete event simulation models (DES). This study has used the combination of Lean and Discrete Event Simulation to improve the processes that are critical to highways and construction processes. The experiments were based on two of the real life pilot projects, and the collaboration of industry participants made it possible to get access to the required data. This investigation has studied the resurfacing process of highways and earthworks process in detail and has experimented with various what-if scenarios to boost the efficacy of both these processes.

Both these processes involve large number of heavy equipment and number of people involved which is a challenge to manage properly. The site arrangements for the resources have to be robust and modifiable to achieve the best possible results.

The objectives of this research work were achieved sequentially by following the design science methodology appropriately. The simulation experiments performed during these studies were suggested by the industry experts and carried significant importance to fully test and publish their results. As expected some of the experimented results were more efficient compared to the current practices and should be implemented in a future study for a practical validation.

This research presented the findings of two simulation models that were developed using the data captured on-site by the researcher and team. The results and the developed model's working are already published so that other stakeholders can benefit from it and modify and use it. The developed simulation models are also published online along with all the instructions to allow other stakeholders to utilize them with little modifications.

Some of the other conclusions are:

- Although the integration of lean and discrete event simulation has been discussed in the literature, its implementation in highways or construction sector has been merely discussed.
- Lean is mostly used in construction and simulation is majorly used by healthcare, manufacturing and processing industries.
- Simulation is used along with lean for its validation and enhanced understanding but not in parallel to maximise their impacts.
- Construction operations are least productive, and most of the projects are delivered outside the time and cost boundaries that can be controlled to some extent using this combination.

- The developed models in this research are applicable worldwide, and people with basic knowledge of computer can utilise them with little modifications.
- These simulation models are of limited scope but can be enhanced further by combining them with risk management, traffic and weather models to obtain a real picture of each case study for superior improvement.
- Simulation models exist in significant numbers and are openly available; but, the majority of them have a very narrow scope and cannot be modified to fit on other projects. However, the models created during this research are generic and can be adjusted according to needs using the guidelines provided with them.

6.4 Recommendations

Even though the research has successfully achieved its aim established in the first chapter, there are still some recommendations which can be drawn for future research to improve these findings.

- There are three paradigms of simulation modelling, i.e. Discrete Event Simulation (DES), Agent-Based Modelling and System Dynamics; however, due to insufficient time and other resources, this study has only investigated the implementation of DES paradigm.
- This investigation has contributed by developing two detailed simulation models based on two separate types of case studies, i.e. Resurfacing and Earthworks. However, construction and highways sector involves various other kinds of processes as well throughout the timeline of a project.

- The data required to create the simulation model was collected from an actual plan in the United Kingdom and validated though experts. However, its implication will be fully established when implemented on another real life project. That can be done by other users, not necessarily the researcher himself.
- Similar models in Simio can be developed for risk management, logistics, traffic management, machines break down and weather restraints etc.
- These new models can then be linked with the lean-integrated simulation models produced in this research.
- Although a simulation model can be integrated directly with lean manufacturing tools for enhanced planning and scheduling, however, it was done separately to avoid complexity and swaying from the scope of research. A future study can look into designing them both together in one working model.
- A future research can perform detailed sensitivity analysis of all the scenarios and publish the results for the stakeholders.
- Some more detailed guidelines and boundaries can be developed in future for each scenario analysed on when these can be effectively applied and when these should be avoided. This will reduce the risk of application of wrong model at a wrong place.

6.5 Summary

This chapter discussed the aim and objectives of this research and how they were achieved stepwise. It started with the introduction of the chapter and then explained all five objectives of the study, what they were and how they were met. After that, it includes a brief conclusion of the whole research journey and finally some recommendations about the future work and how the scope of this investigation be enhanced and how its implementation can be facilitated in the construction and highways sector.

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Appendix 1: Simulation Graphics

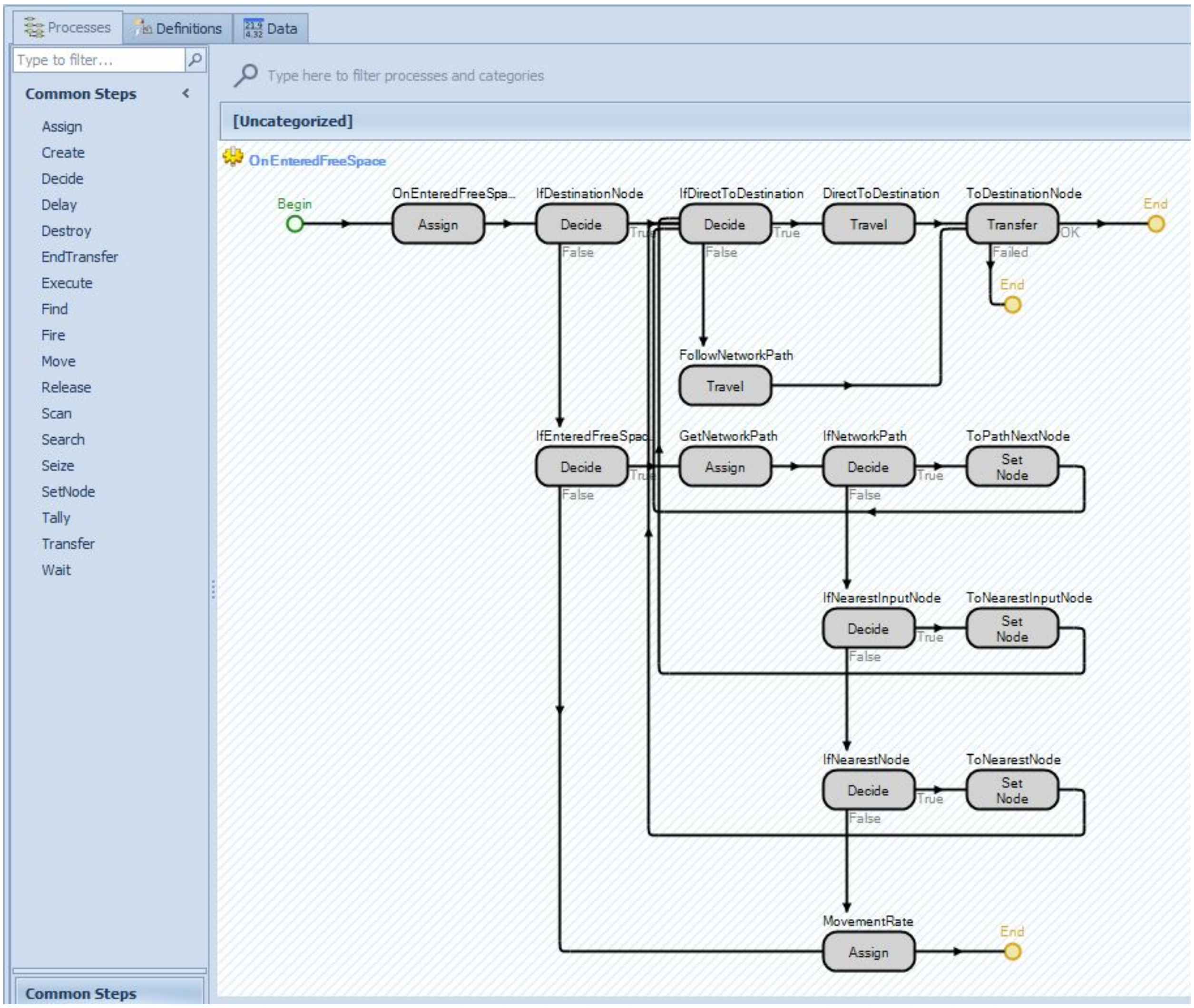

Figure 8.1 showing the background process of earthworks simulation model

Appendix 2: DES model specifications

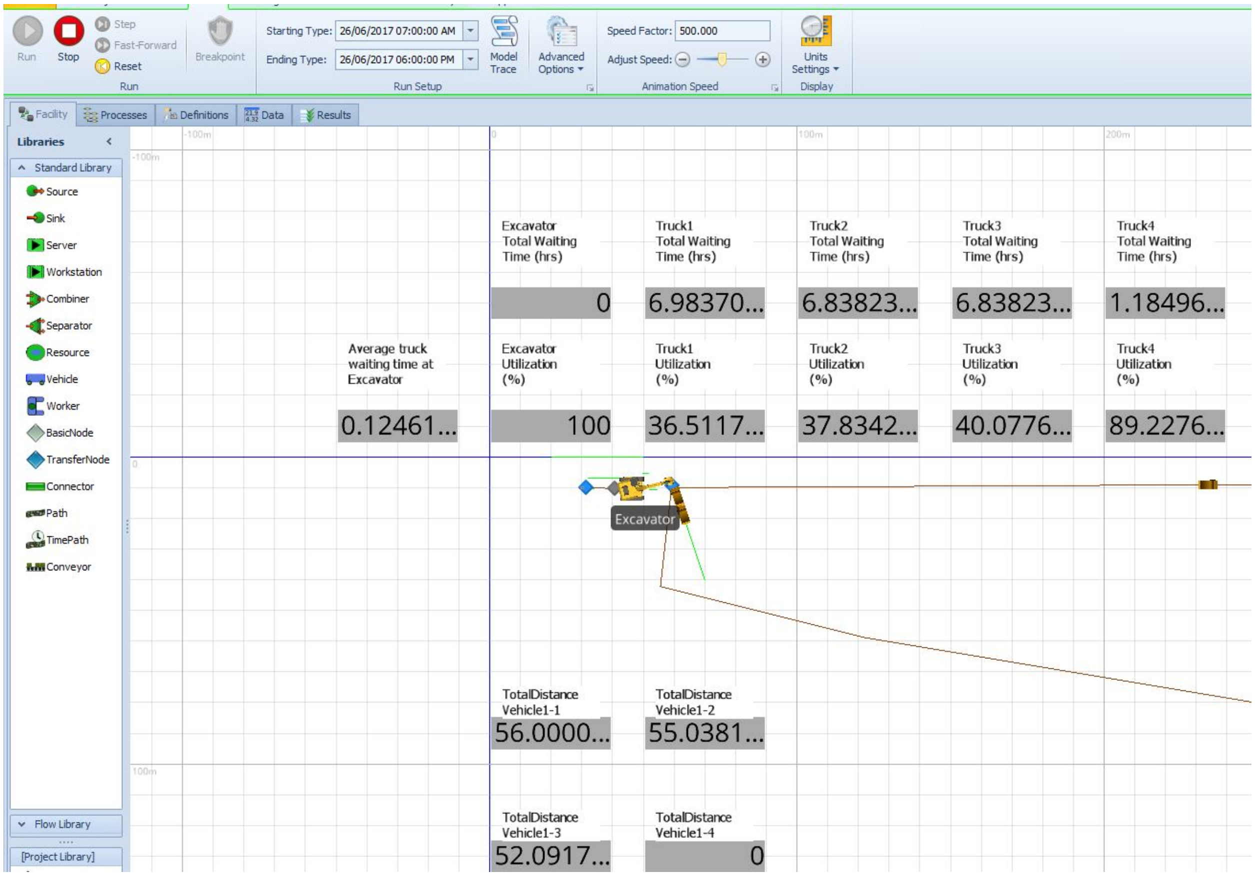

Figure 8.2 showing the user interface of the Simio software used in earthworks case study

Appendix 3: Interview Questionnaire

Questionnaire

Section 1: Demographic section

1. What is your current job position?
a) Engineer
b) Project Manager
c) Head of the section
d) In charge of department
e) Other (please elaborate)

2. What type of Education qualification do you hold?
a) Diploma
b) Bachelors
c) Master
d) PhD
e) Other (please elaborate)

3. What research area describes you best about qualification?
a) Civil engineer or architect
b) Mechanical engineer
c) Finance
d) Accounting
e) Other (please elaborate)

4. For how many years have you worked in this department
a) 1 - 5 years
b) 6 -10 years
c) 11 - 15 years
d) 16 - 20 years
e) More than 20 years

5. What is your area of job at the moment?
a) Procurement
b) Engineering
c) Finance
d) Process Improvement
e) Other (Please elaborate)

Section 2: Implementation of DES (Discrete Event Simulation) in your organisation.

1. Does your department use DES for as-is process improvement tool?

a) Always implemented
b) Sometimes
c) Not implemented
d) I don't know
e) We have other tools e.g. lean

2. How often is the DES used before starting the construction work on site?

a) Never
b) Rarely
c) About half of the time
d) Most of the time
e) Always

3. How do you utilise DES or similar computer based simulation techniques?

a) In planning stages along with Value Stream Mapping.
b) Before starting the project.
c) During the work happening on site (as-is improvement analysis)
d) Post work analysis (use lessons learnt for future projects)

4. How is DES implemented in your organisation?

a) By process improvement people
b) Project engineers working on the projects
c) External people (organisations) hired
d) Other (please elaborate)

5. What are the main types of exercises related to process improvement that your department conduct to assess the efficiency in any project?

a) Discussions based exercises
b) Live exercises with various trials
c) Lean techniques implementation
d) Other (Please elaborate)

6. Who is responsible for process improvement activities in your organisation?

a) Project manager
b) Lean manager
c) Project Engineers
d) Project planners
e) Others (please elaborate)

Section 3: Effectives of Discrete Event Simulation (DES)

1. Some other mathematical tools can manage to model a steady state scenario and Simulation effectively is not really required. Do you agree with the statement?

a) Agree
b) Highly agree
c) Disagree
d) Highly disagree

2. DES models created by different simulation tools can be applied to real life situations and projects for process improvement purposes. Can they be really performed in real life situations?

a) Yes
b) Yes, but after approved by experts.
c) No
d) It depends

3. What are the strengths (most right sides) of any DES model that represents a real life situation?

a) Data collection techniques
b) As-is situation capturing
c) Graphical work
d) Analysis performed

4. Can you rate the following factors/statements accordion to your knowledge and experience?

No.	Effectiveness of Discrete Event Simulation (DES) techniques	Rating				
		Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Discrete Event Simulation is time-based and takes into account all the resources and constraints involved, as well as the way these things interact with each other as time passes on construction projects.					
2	Has DES been appropriately applied in highways sector?					
3	Highways sector is more like manufacturing sector rather than construction. Hence the optimisation techniques in manufacturing can be replicated in highways sector as well.					

4	DES can be implemented in all stages of project lifecycle i.e. planning, before starting, during construction and post project reviews.					
5	Some other mathematical tools can manage to model a steady state scenario and Simulation effectively is not really required.					
6	DES in highways has not been used as it has been utilised in manufacturing, healthcare, production and processing industries.					
7	When you make changes to the simulation, you see exactly how the system would behave in real life. This can improve construction processes.					
8	Simulation approaches are particularly well equipped to help users diagnose issues in complex environments.					
9	Many systems improvement ideas are built on sound principles, proven methodologies (Lean, Six Sigma, TQM, etc.) yet fail to improve the overall system. A simulation model allows the user to understand and test a performance improvement idea in the context of the overall system.					
10	Simulation modelling is commonly used to model potential investments. Through modelling investments, decision-makers can make informed decisions and evaluate potential alternatives.					

Section 4: Analysis of this Case study work (performed by researcher)

1. How accurate is the discrete event simulation model?
a) Very accurate
b) Accurate
c) Inaccurate
d) Need major changes
e) Other (please elaborate)

2. Are the what-if scenarios practical? Can they be really performed in real life situations?
a) Yes
b) Yes, but after minor changes
c) Yes, but after studying the process is more detail
d) No
e) Other (please elaborate)

3. What are the strengths (most accurate aspects) of this DES model?
a) Data collection techniques
b) As-is situation capturing
c) Graphical work
d) Analysis performed
e) Other (please elaborate)

4. What kinds of changes are further required in this discrete event simulation model?
a) Data collection techniques
b) As-is situation capturing
c) Graphical work
d) Analysis performed
e) Other (please elaborate)

5. By looking at this particular DES model, what are your thoughts about this? Can you please rate them in the table below?

No.	Analysis of DES model developed for this case study work.	Rating				
		Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

1	Has the integration of lean and discrete event simulation been utilised appropriately in this particular scenario?					
2	Has the data been collected in an appropriate way to understand the as-is situation of work fully? DES model has been created after studying the right stage of work i.e. as-is analysis.					
3	Data analysis has been performed in a professional manner. No details were ignored?					
4	Assumptions made during the creation of DES model are practical, and they will not affect the working of the model in real life scenario.					
5	DES has been applied in the right stage of the project lifecycle. I.e. as-is analysis was done, and this simulation model can help in future projects.					
6	Some other mathematical tools could also have done the similar work and capture all the minor details like performed here.					
7	This simulation model requires further changes before it can be replicated in real life scenarios.					

6. How do you think this model can further be improved? Please discuss in detail.

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Appendix 4: Journal Article

Construction Innovation

Improving productivity of road surfacing operations using value stream mapping and discrete event simulation

Zeeshan Aziz, Rana Muhammad Qasim, Sahawneh Wajdi,

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Improving productivity of road surfacing operations using value stream mapping and discrete event simulation

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Zeeshan Aziz, Rana Muhammad Qasim and Sahawneh Wajdi
School of the Built Environment, University of Salford, Salford, UK

Abstract

Purpose – The purpose of this paper is to investigate the integration of discrete event simulation (DES) and value stream mapping (VSM) to enhance the productivity of road surfacing operations by achieving high production rates and minimum road closure times. Highway infrastructure is one of the most valuable assets owned by the public sector. The success of national and local economies as well as quality of life of the general public depend on the efficient operations of highways. Ensuring smooth traffic operations requires maintenance and improvements of the highest standard.

Design/methodology/approach – Research approach involved the use of primary data collected from direct observation, interviews, review of archival records and productivity databases. Based on this, process maps and value stream maps were developed which were subsequently used to produce discrete event simulation models for the exploration of different optimisation scenarios.

Findings – This research highlights the synergistic relationship between VSM and DES in driving innovation in construction processes. Identified factors that affect roadworks process productivity include machine, manpower, material, information, environment and method-related factors. A DES model is presented to optimise the process and increase the production rates. A hybrid DES-VSM approach ensures an integrated approach to process optimisation.

Research limitations/implications – This study is an application of hybrid version of previously published DES-VSM framework in the manufacturing sector. The present study has extended and tested its applicability within road surfacing operations. The different what-if scenarios presented in this paper might not be applicable to other parts of the world owing to various constraints. The study has focused on addressing the waste production inherent in pavement laying process. Even though external variables could possibly influence pavement process, those were ignored to allow for in-depth focus on the process under consideration.

Practical implications – Road users are one of the most important stakeholders that will benefit from the positive implications of this study. Private resurfacing companies and transport departments can optimise their overall process and style of working by comparing their end-to-end process and work plans with the ones mentioned in this paper. It will boost the productivity of equipment like planners, pavers and other machines used for resurfacing operations.

Originality/value – Existing approaches to process modelling such as VSM and process diagrams are constrained by their effectiveness in the analysis of dynamic and complex processes. This study presents a DES-based approach to validate targeted improvements of the current state of road surfacing processes and in exploration of different optimisation scenarios.

Keywords Productivity, Simulation, Process improvement, DES-VSM framework, Paving, Road Surfacing

Paper type Research paper

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1. Introduction

Road surfacing is an important component of highway development and maintenance. Highway construction sector, in general, is characterised by its slow pace of change, low productivity, waste, fragmentation and long-established processes and ways of doing business which has not changed over decades. Efficient running of road network has the success of national and local economies as well as the quality of public life dependent on it. Increasing volumes of traffic require maintenance and improvements of the highest standard. For instance, the National Infrastructure Plan (NIP) by HM Treasury, United Kingdom (2015), has detailed the existing commitments leading to the construction of at least 52 major road projects by 2020-2021, addition of over 750 lane-miles of capacity to the busiest motorways and trunk roads and resurfacing of about 80 per cent of the strategic road network (SRN) by 2020. Such huge public-sector investments in road infrastructure come alongside the government's cuts in operations and maintenance expenditures on infrastructure owing to macroeconomic challenges facing the economy. Thus, a key challenge is to deliver major road schemes in resource-constrained environments while maintaining safety, cost efficiency, sustainability and minimal impact on road users. Enhancing the productivity of existing processes is the key to successfully operating in a resource-constrained environment.

Recent reviews of the construction productivity performance, specifically roadworks, indicate that the industry has fallen short in comparison to manufacturing- and services-based industry sectors. Some of the key factors restraining the productivity of construction are related to quality, use of project controls and proper levels of supervision. Similar observations were made in the annual UK Construction Industry Performance Report (2015), indicating that majority of construction projects continue to fail to meet their time and cost targets. These observations are often coupled with falling profitability and client dissatisfaction with regards to product quality, service and value for money. As explained by Jergeas (2009), excessive time extensions, over budgeting and lack of productivity are connected with the conduct of major capital construction projects worldwide. Several researchers and practitioners have recognised poor management practices that cause poor performance, namely, scope changes, lack of proper planning and scheduling, design errors and omissions, inadequate management of tools, equipment, materials and labour, in addition to many other factors. Resulting road closures result in negative feedback from road users.

Considering the aforementioned findings, there is an urgent need for improving the productivity of roadworks projects within the construction industry to deliver ongoing and future projects with maximum efficiency and minimum waste. To address the issue of efficiency, various opportunities have been realised in the highway sector. Discrete event simulation (DES) coupled with value stream mapping (VSM) has been recognised as a technique to improve the overall process as well as some specific key areas. Manufacturing, process, construction and healthcare sectors have advanced their processes and benefitted from either simulation, VSM or the integration of both.

The rest of the paper is organised as below. Section 2 presents a literature review, while Section 3 introduces readers to the analysed case study. Section 4 introduces different scenarios of DES model. This is followed by discussions in Section 5 and finally the conclusions.

2. Literature review

Literature review discusses the relationship between DES and VSM, how they both complement each other and the relevance of the relationship in supporting highway operations. The synergic relationship between VSM and DES has been tested and applied before in manufacturing and construction industry. However, its usage in resurfacing and asphalt industry has not been adequately explored. Table I presents a summary of key previous literature published within the road resurfacing context. Published literature focuses on the logistics involved in resurfacing operations and does not adequately cover the hybrid VSM-DES relationship in resurfacing of road pavement.

VSM was formed using Toyota production system and lean manufacturing principles (Womack *et al.*, 1990). It is defined as an iterative method used to map and analyse value streams, and its goal is to evaluate and communicate production process aspects such as material and information flows, as well as non-value-adding actions (Rother and Shook, 2003; Lasa *et al.*, 2008). It is used in improvement schemes like increasing throughput and in reducing the lead time and work in progress (WIP) (Alvarez *et al.*, 2009). VSM is made up of three components:

(1) Current State Gap that visualises value-adding and non-value-adding activities in a process;
(2) Future State Design, a value stream that solves the identified problems of current state; and
(3) Yearly Value Stream Plan that creates an operational plan to reduce the gap between the present and future states (Martin and Osterling, 2014).

VSM, however, cannot provide hard facts for decision making and simply points towards a direction. It lacks the ability to forecast the effects on future performance of a system analytically. Hence the need for simulation arises to experiment and evaluate the future behaviour of a scheme (Erikshammer and Weizhuo, 2013). Basic lean tools, including VSM, are sufficient for analysing simple and linear processes with relatively consistent demand patterns. Static approaches are incapable of analysing processes that incorporate volatile demand dynamics, mixed product complexity or the shared use of resources. In such scenarios, time dependencies are important as a process simulation model can accurately describe and visualise the dynamics of the process, its performance and the required resources.

Simulation is the process of modelling a real-world situation and developing a framework within which the system can be analysed (Law and Kelton, 2000). Application of simulation in construction operations has many advantages including estimation of possible delays, productivity determination and improvement, in addition to resource management and optimisation, stochastic system response to unexpected conditions and ability to respond to random and dynamic features while the system is operating (Halpin, 2003). Simulation is also defined as a "controlled statistical sampling technique (experiment) that is used, in conjunction with a model, to obtain approximate answers for the question about complex, multifactor probabilistic problems" (Lewis and Orav, 1989). This technique is used by many industries to model real-life and hypothetical situations, owing to its dynamic nature and complex scenarios. This was also acknowledged by Bhasin, 2015, stating that as an integral part of a lean activity, companies spend much time designing new process layouts, producing CAD drawings and building process maps en route. The cost of these activities can run into significant amounts even when none of these outputs will indicate whether the new process will succeed. That is the job of process simulation, which can examine the capability of the new design and provide vital implementation support to decision makers that they are on the right path.

The integration of VSM with DES is more dominant in manufacturing industry than in construction. Simulation-based VSM makes it possible to investigate complex systems and

References	Industry	Findings	DES	VSM	DES-VSM framework
Marzouk and Fouad (2011)	Highways, Resurfacing	This paper only uses simulation for improvement in traffic flow while resurfacing happens under lane closure condition. It does not mention VSM or the holistic view of overall process	✓		
Xie and Peng (2012)	Healthcare	Integration of simulation and VSM can analyse alternatives for problems of capacity planning and schedule control and improve healthcare operations			✓
McDonald *et al.* (2002)	Manufacturing	DES can be a vital part of VSM to complement future design			✓
Lian and Van Landeghem (2007)	Manufacturing	Integration of DES with VSM improves information for process design			✓
Agyapong-Kodua *et al.* (2009)	Manufacturing	Transforming static VSM models to dynamic DES increases validity and reliability of future design			✓
Marvel and Standridge (2009)	Manufacturing	DES provides validation and visualisation of VSM future design			✓
Singh and Sharma (2009)	Manufacturing	VSM is a powerful tool for lean manufacturing and allows firms to continuously improve their understanding of lean processes		✓	
Yu *et al.* (2009)	Construction	Combination of DES and VSM increases understanding of behaviour of future design			✓
Gurumurthy and Kodali (2011)	Construction	DES validates, approves and visualises VSM future design			✓
Erikshammer and Weizhuo (2013)	Construction	VSM is unable to analytically evaluate performance of future state design without the help of DES			✓
Labban and Haddad (2013)	Construction	Although research into simulation of construction continues to advance and thrive in the academic world, application of simulation in the construction industry remains limited	✓		
Abdulmalek and Rajgopal (2007)	Process	Data obtained from DES evaluates and validates VSM process design			✓
Seth *et al.* (2008)	Process	VSM serves as a starting point to help management, engineers, suppliers and customers recognise waste and its sources		✓	

Table I. Synergistic relationship between DES and VSM and its popular applications interpret the simulation results in a language that lean recognizes (Solding and Gullander, 2009). Both DES and VSM provide a holistic assessment of a system, and DES also adds a fourth dimension, time, to VSM. This combination offers insights that may have been missed if VSM alone had been used (Donatelli and Harris, 2009). It has been noticed that DES can enhance VSM and a process can benefit incredibly with the integration of both (Erikshammer *et al.*, 2013). The main purpose of using their integration is to boost the productivity of resurfacing process, reduce waste and maximise the efficiency of resources involved in the process.

Productivity is described as the ratio of outputs to inputs used in the production process. In other words, it is the output per input unit. Slitherers (2009) described productivity in the manufacturing industry as a "measure of the output compared to the input". However, productivity in construction can be defined in terms of many factors such as performance, productivity rate and unit person-hour (p-h) (Dozzi and AbouRizk, 1993). A definition of productivity in the construction industry was presented by Merrow *et al.* (2009), using three approaches: the economic approach, a construction manager's approach, and the project approach. The economics approach measures labour productivity regarding the economic output per hour worked. The construction manager's approach measures productivity at activity level by determining the work done per hour at the team or individual level. Finally, the project approach measures the productivity of the entire project as a unit of observation. Dozzi and AbouRizk (1993) stated that productivity has two significant measures which are the efficient use of labour and the relative competency of labour to achieve what is required; the latter is the most important to contractors and organised labour. Rebholz *et al.* (2004) defined productivity in road construction industry as the quantity of laid asphalt in tonnes per hour or per day. For purposes of this study, this definition was adopted.

3. Methodology

The key focus of this effort was improving the productivity of the road surfacing process. The study drew upon lean theory and tools to improve road resurfacing operations. There are approximately 40 lean tools that are being used in diverse operations worldwide, and they all have different styles of operation. Some of the common tools are 5s, Andon, Last planner, Single Minute Exchange of Dies (SMED), Kanban, VSM, process mapping, visual management and Kaizen. This study, however focused on VSM and attempted to improve and validate it with a simulation technique. The reason for choosing VSM was its frequent application in highway operations. VSM is used to visualise and map the processes leading to the attainment of high production levels. However, as mentioned in the literature review, there are various weaknesses and drawbacks of VSM that can be eliminated through the application of DES. The gaps and loopholes in value stream maps of resurfacing operation were diagnosed with the help of fishbone analysis.

For validation of VSM, a simulation technique was adopted. The main three types of simulation are *discrete-event, continuous and Monte-Carlo*. They were defined by Nance (1993) as *discrete event simulation (DES)*, which uses a logical model of a real-life physical system representing state changes at precise points of the simulated time. Both the nature of the state change and the time at which the change occurs dictate an accurate description. A *continuous simulation,* which is based on the equational model, rarely represents a real-life system and does not represent the precise time and state relationships arising in discontinuities. The objective of researches conducted using such models has no requirement for the explicit representation of state and time relationships. A *Monte-Carlo simulation,* which uses models of uncertainty and representation of time, is required. The term originally attributed to a situation in which a difficult non-probabilistic problem is simulated through the presentation of a stochastic process satisfies the relations of a deterministic problem.

For the purpose of this study, DES was chosen because of the flexibility and precise state fluctuation within the process. While multiple DES software applications have been introduced into the market by different developers, such as *FlexSim, Simio, Anylogic, JaamSim, MASON, Sim.JS* and many others, *FlexSim* was selected to carry out the intended simulations considering it is one of the most popular simulation software applications for its ease of use, rich functionality and capabilities of tracking different data points such as throughput, content, machine state and utilisation. According to Manuj *et al.* (2009), there are seven major steps in the methodology of creating a simulation of a real-life situation of a system:

3.1 Problem formulation

This step involves defining overall objectives and answering questions specific to the simulation model. According to Keebler (2006), this is a critical step, and lack of attention in this phase can lead to let-down in model's performance. If the problem is not stated precisely or in quantifiable terms and the purpose is ambiguous, it will lead to time wastage, incorrect analysis, unfitting decisions and incorrect inferences (Dhebar, 1993). It is a good exercise to consult individuals who are involved in the problem to address it properly. It will not only help in defining the scope but also aid in establishing the key performance indicators (KPIs), time limits and required resources.

3.2 Selection of dependent and independent variables

Dependent variables show the performance measures, and independent variables include the system parameters. Independent variables are manipulated, and their effects on dependent variables are logged and investigated in a simulation model. The values of dependent variable provide answers to the problem formulated in Step 1. As the outcome of a model depends on what is included in it, the objective of the research and specific questions guide the selection of dependent and independent variables. Various variables can influence the simulation, including legal, technical, economic, organisational, managerial, monetary and historical factors (Towill and Disney, 2008).

3.3 Development and validation of conceptual model

According to Banks (1998), a conceptual model is an abstraction of the real-life system under examination. It uses logical and mathematical relationships related to the components and structure of system. Unambiguous assumptions and specified descriptions in the conceptual model ensure that the model is developed in accordance with the problem statement. The validity of the outcomes directly depends on the inputs in the system, and therefore, it is important to develop a conceptual model for validation prior to investing resources in a computer-based model.

3.4 Data collection

This step can be challenging as data might not be readily available or in required formats. Sometimes the level of detail is inappropriate and this step is performed in parallel to the development of the conceptual model. Data requirements must be established first to define system parameters, layout, probability distributions and operating procedures. Data can be obtained from company databases, surveys, interviews and other published sources. In some cases, data can be generated using a computer if the actual data can be approximated using distributions like Poisson, normal and exponential methods. Theses data are the backbone of the whole work, and any mistakes in this step will nullify all further analysis.

3.5 Development and verification of computer-based model

Computer modelling begins simply, and complexity can be added in steps until a model of adequate detail and complexity has been created (Banks, 1998). Verification is performed to check whether the computer application of the conceptual model is correct. According to Sargent (2007), verification is a continuous process, and it needs to be performed concurrently with the development of the computer model rather than at the end. Verification means analysis of outputs, debugging of errors and checking the code. There are two benefits of verification:

(1) identification of undesirable system behaviour; and
(2) checking whether the complex steps can be replaced with simpler ones (Fishman and Kiviat, 1968).

Various software are available in the market to create and verify a simulation model.

3.6 Model validation

Model validation is a process of establishing whether a simulation is accurately representing the system under investigation. This validated model can then be used to make decisions similar to what the system could perform if they were feasible and economical to experiment (Law, 2006). An invalid model cannot be trusted as it may lead to erroneous conclusions. There are various ways to validate a model, including consulting academic scholars and practitioners, focus group interviews and performing sensitivity analyses.

3.7 Simulations

At this stage, various scenarios are run in the simulation with changing dependent and independent variables. For each system configuration of interest, decisions are made on the number of independent model replications, size, warm-up period and run length. In a simulation, sample size can be increased by increasing the number of simulation runs for each condition, reducing the length of subintervals and increasing the length of the run to increase the number of subintervals (Bienstock, 1996).

A similar method is used in this study. However, what differentiates this study from other works is the use of VSM. The figure below shows the methodology used for the creation of conceptual framework, verification, data collection, development and validation. Figure A1 shows the framework developed for this particular work.

4. Case study analysis

This section presents a detailed case study of a road surfacing process improvement project at the project level, involving the use of lean tools alongside DES to explore the opportunities of optimising the existing road surfacing process.

All types of roadwork processes, whether new constructions or maintenance work, are classified into two major types, i.e. surfacing and resurfacing. Every road surface has its diverse characteristics which vary according to its geography, location, surrounding terrain, speed-related parameters, intended use and type of pavement. A typical comprehensive resurfacing process of a hot mix asphalt pavement is shown in Figure A2 (Area 9 Pavement Process Improvement, 2015). Key constraints that must be addressed before the start of pavement process include setting up of traffic management system (typically 15 min), material call-off and planner mobilisation (typically 30 min) and planning a head start (typically 45 min), leading to a total non-value-adding, pre-paving time of 1 h 30 min. Key post-pavement process constraints include rolling (typically 30 min), cooling and curing (typically 75 min) and traffic management system removal (typically 30 min). This means a total of 2 h and 15 min post-paving shift period. A safety margin of around 1 h 30 min is set for safety-related activities. Installation and removal of traffic management system has an average duration of 30 to 45 min and depend on a wide range of variables including the use of different designs and types of traffic management systems, delays and operator-/process-related variables.

Analysis of archived data and that collected from on-site observation was used to build a situation summary and current state of the process as discussed below:

(1) The average output for a paving team is 240 tonnes per shift.

(2) A paver can lay 130 tonnes per hour when it is operational. This equates to 1.8 h of value-adding activity in a typical shift (240 t/130 t = 1.8 h of value-adding work).

(3) Utilisation of plant and people based on a 10-h paid shift:
- Planning team: 137/600 min = 22 per cent utilisation;
- Sweeper (same as planning above) = 22 per cent utilisation;
- Spraying (nominal utilisation as this is a very quick operation);
- Paving team utilisation = 108/600 min = 18 per cent utilisation;
- Rolling (same as paving above) = 18 per cent utilisation;
- White lining = 60/600 min = 10 per cent utilisation;
- Trucks removing planning and delivering blacktop = 30-40 per cent; and
- Aggregate plant = circa 20-40 per cent utilisation.

(4) Eighty-six per cent of the time paving teams work within a 7-8-h work window.

(5) Fourteen per cent of the time paving teams work in excess of this window: between 9 and 10 h.

(6) There is an average 23-min delay between the placement of a traffic management system and the start of the first value-adding activity.

(7) Analysis of past six months data indicates that the total paving activity (plane, pave, sweep, spray and roll) take up approximately 3 h 54 minutes or between 50 and 57 per cent of the available work window.

Figure A2 shows the "As-Is" process as a bar chart based on data observed at two site visits and supported by historical data. Key value-adding activity (i.e. paving process) ran for just 2 h 11 min in an 8-h work window (10 p.m. to 6 a.m.) and 10-h worker shift (9 p.m. to 7 p.m.). A total of 298 tonnes over a stretch of 938 m was laid in 2 h 11 min of value-adding activity, leading to an hourly tonnage rate of 137 T and pavement productivity of 33 per cent. While the work window was up to 6 a.m., the traffic management system was removed at 4:39 a.m., leading to 1 h 29 min' lesser utilisation of the allocated work window.

Figure A3 above shows the value stream map of the as-is operation. Based on it, various opportunities for waste reduction can be identified. Firstly, planning operation started at 22:37 when site access had been granted at 22:08, signifying a delay of 29 min. Secondly, main value-adding activity, i.e. paving, started at 00:17. This highlights a paver sitting idle for over 2 hours, awaiting material arrival. Thirdly, while the work window was up to 6 a.m., workers were off-site about 1 h 21 min before the allocated period, highlighting another area for improvement. Finally, there was a possibility of extending the work window by obtaining an early access to work. Figure A4 below shows the as-is (baseline) process with respect to time.

4.1 Identification of problems

In the problem definition phase, several collaborative workshops and meetings were held with all key project stakeholders involved in the process. Using a team-based approach, various process optimisation opportunities were discussed, key findings from the research were discussed, key constraints affecting the output were analysed, and opportunities for improvement were identified. A key challenge considered by the team was to increase the output and production rates without the deployment of any additional resources. This was done primarily by addressing constraints that primarily affect the flow of work. Improved productivity was to be achieved whilst addressing key constraints of safety (for both operatives and road users), resource wastage (e.g. ordering aggregate materials earlier than usual also increases the risk of material wastage if work is abandoned because of road accident or weather), quality (e.g. increasing paver speed to enhance productivity could have negative consequences for quality), on-time traffic management system removal (to avoid risks of late road openings of busy roads) and operative staff buy-in (in terms of longer working hours and different working methods).

4.2 Steps taken

To reduce time wastage between motorway closure and the start of planning operation, various opportunities for improvement were identified. First, by enabling an early contact between regional traffic control centres helped speed up the process and reduce the waiting time involved in the clearance process. The second area of improvement identified was to set out the traffic management system to close two lanes earlier (given safety constraints are addressed) and bring plant material ahead of full closure. This ensured that plant material was available ahead of full motorway closure. To increase the productivity of pavement process, calling material earlier would allow the paver to begin operations early. There was a time lag of 14 min between the commencement of planner and paver processes, allowing time for cleaning and preparation.

The third area of improvement involved early removal of traffic management system with workers going off-site by 4:39 a.m. There is scope to make the best use of work window by ensuring work continues close to 6 a.m., the allocated work window. Given the fact that paver utilisation in an average shift is just 33 per cent, doubling pavement productivity by addressing constraints (e.g. earlier mobilisation of paver, full utilisation of work window) has the potential to double the paver productivity and, thus, the output. Also, the possibility of extending the work window, particularly over weekends or public holidays, when lesser than average traffic volumes are expected could provide an opportunity to increase productivity. An improved work diagram is shown in Figure A5. It shows an increased work window of 10 hours and 36 minutes. The total asphalt tonnage laid was 1,024 tonnes, in comparison with 298 tonnes laid in the baseline process (Figure A4).

Table II above shows the differences in efficiency between baseline and improved process state. In resurfacing operations, paving is the most important activity, and its duration can highly impact the productivity. It can be seen that paver productivity increased from 33 to 64 per cent leading to 2,700 m of the paved road compared to 938 m on average.

4.3 Data collection for simulation

At this stage, an improvement scheme was implemented, and there was an opportunity to record the data required for the development of the simulation model. Data was required from various times and levels (e.g. present-day data, traffic counts, historic data from aggregate industries, trucks and other equipment data). Most of the process-related information was captured by people present on site in the form of videos and time lapse pictures. This information was then fed to the simulation for better accuracy and validity. Figure A6 below shows the data collection steps and procedures that were required for the development of this simulation model.

4.4 Root cause analysis

This section presents a root cause analysis from six different perspectives, with an end objective to improve the total production per shift. Figure A7 helps understand the current issues facing a surfacing operation system as well as provides project strategy ideas to improve the output. A fishbone (Ishikawa) diagram shows many constraints, identified in the road surfacing process review, and their causes. The fishbone diagram was chosen because of the need to study and analyse the possible reasons that can negatively affect the process output target. The four W's need to be answered and considered to analyse the fishbone diagram. "What" refers to questions related to objects such as materials and machines. "Why" is used to answer questions regarding work conditions such as motivation of manpower. "When" refers to problems related to time sequence in operation such as time needed for production. Finally, "Where" is concerned with effects related to the place, production line, loading area and so on. Figure A7 shows the different factors that were regarded as constraints and were considered responsible for low productivity.

4.4.1 Materials. Key raw materials included asphalt and aggregate. Key risk factor was reliance on a single supplier. Having an alternative supplier list provides more flexibility. Another constraining factor is the aggregate plant capacity, which also can have a major effect on the aggregate supply required to reach the target outputs. Other factors contributing to the production output include the availability of trucks to deliver materials and the number of deliveries they can make.

4.4.2 Machines. Machines refer to the equipment, technology and tools required to perform the process. During road surfacing, many machinery and tools are used, such as paver, roller, planner and pitch spraying machine. Following are some of the identified risks associated with machines:

- the capacity of the aggregate plant is limited to the night-time work window it needs to operate within;
- changeover times within the laying process can have a big impact on the output;
- machines can suffer breakdowns and need maintenance periodically during the laying process; and
- set up of any machine if not performed before material delivery will create a delay in the process.

Processes	Baseline process	Improved process
Shift duration	10 h	10 hours (staggered)
Work window (Theoretical)	8 h (22:00 to 06:00)	13 hours (20:00 to 9:00 a.m.)
Work window (Actual)	6 h 31 min (22:08 to 04:39)	10 hours 36 minutes (21:03 to 7:39)
Tonnage laid	298 tonnes	1024 tonnes
Paving duration	2 h 11 min	6 h 50 min (22:15 to 5:05 a.m.)
Average hourly tonnage laid	137 tonnes (@45-mm thin surfacing)	149 tonnes (@45-mm thin surfacing)
Pavement length laid (in meters)	938 m	2,700 m
Paver productivity (i.e. Paving Time/Full Working time)	33 (%) (2 h 11 min/6 h 31 min)	64 (%) (6 h 50 min/10 h 36 min)

Table II. Improvement comparison

4.4.3 Manpower (people). Site operatives need to have an adequate intellectual and physical capacity to cope with long duration shifts, varying from 8 to 13 h. Moreover, paving operations require high attention to details such as alignment of the asphalt truck to the paver. Furthermore, operator's reliability is necessary to perform the process without errors. In this context:

- shift patterns can be a limiting factor;
- since the working window was extended, more than one shift might be required. That could mean working part shifts, which may be inefficient or impractical;
- the operatives lose out and may resist different and longer working hours for the same pay; and
- people and management may be a constraint as they currently tend to avoid risks; this can change over time.

4.4.4 Method (process). Methods refer to the performed process and the particular requirements for performing them. Lean production plays a major role in increasing the productivity and product quality while reducing the waste and cost. Key factors include the following:

- the type of contract will influence behaviour;
- approach to risk, giving confidence to all concerned;
- programme planning, which can positively affect many of the above constraints through balanced planning; and
- picking the right team configuration specific for each type of job.

4.4.5 Information (measurements). Measurements or information refers to the data generated from the different processes that are used to evaluate quality:

- Loops will affect the process. However, the said loops affect tonnage but not necessarily utilisation.
- Most of the improvement made would also improve the loop process, in that more could be done on each shift.
- The design of the product will affect the process, i.e. deeper surfacing may require periods of curing between layers.
- Figure A8 shows the root cause analysis in the form of a fishbone diagram for better understanding and visualisation.

5. Simulation model design

The definition of the simulation scope is crucial for defining the analysis boundaries. Clearly defined scope of simulation system and boundaries could result in more useful simulation. The scope of simulation development in this study was limited to the activities involved from the start of road surfacing activity (i.e. from the time of road closure for surfacing purpose) until the road is open again. Programming of the project, the constraints of material deliveries or what goes on at asphalt plant/quarry level are beyond the scope of the presented simulation.

After defining the boundaries, it is important to identify the key assumptions about how the system being studied acts together with its defined external environment (Beaverstock *et al.*, 2014). The following assumptions were considered in building the simulation model. Preparation and logistic activities were included in the model, taken as fixed timings as measured on site, and are not part of the analysis. The simulated operation activities included planning, sweeping and pitch spraying, paving, rolling, white-lining and testing. Any sub-activities within each one of these activities were not considered. All the materials required in the process were assumed to be always available and delivered on time. Downtime of equipment was not included in the simulation. Also, the simulation was based on paving 45-mm thick surface course. Figure A9 shows the simulation model developed using the software called *FlexSim*. Figure A10 shows the 3D simulation of the equipment and process.

The research has focused on addressing the waste inherent in pavement laying process. Even though external variables could possibly influence the pavement process, those were ignored to allow for in-depth focus on the process under consideration. This has been acknowledged as one constraint of the analysis presented.

While modelling the random elements within the road surfacing process, it is important to replace time certain components with a probability distribution. Three randomly distributed components were used: asphalt inter-arrival delivery, asphalt truck position time and paving times. When analysing the system using simulation, times from these distributions can be "sampled" and used to recreate a typical cycle of the process. The simulation of multiple cycles can then provide attributes of a particular operative set-up, such as overall time and average planning or paving rates. To obtain a realistic simulation model, actual data from site operations was used. According to Smith (1998), the following steps are involved in modelling a simulation:

- gathering actual data;
- probability distribution selection;
- generation of variates (random samples) from these distributions;
- simulation of resurfacing operations; and
- experimental analysis of surfacing operations.

To determine the probability distributions used to model the resurfacing process, historical data collected over 115-night shifts over a six months' period was used. To select the suitable probability distribution, the historical data were analysed and tested against Anderson–Darling normality using a statistical distribution software application *Minitab 17*. As the paving process constitutes a major operation, other subsidiary processes such as planning were assumed to match the production rate of the paver. However, detailed analysis of the data indicated the average time for planning was 2.17 tonnes/minute and the average time for paving was 2.19 tonnes/minute (Figure A11).

The following calculations were done to have unified units for use in *FlexSim:* The process flow item is assumed to be equal to 1 tonne of asphalt. For paving, the average paving rate is 2.19 tonnes/min i.e. 131.4 tonnes/h, which means that 1 tonne requires 27.40 s to be paved.

Paving is a rehabilitation process and is not treated as a typical construction project. It has more resemblances with manufacturing when observed as a process. Using common distribution in manufacturing processes is prevalent. Further, the authors needed to find the average output of a typical paver to simulate various what-if scenarios. These calculations were done manually and then validated using the Anderson–Darling test. This is the reason common distribution was used here instead of beta, which is usually used in construction projects.

5.1 Simulation outputs and validation

With a small difference in values, the simulation outputs confirmed the need to improve the current state as the percentages of paver utilisation were considered to be low compared to the permissible work window of the shift. The paver was working only for 38 per cent of the time starting from road closure until the road was open again (Figure A12). These outputs and percentages provided a credible evidence of the waste inherent to the process of road surfacing. It can be concluded that the major waste in the process was in the form of "waiting" for the paver to start processing (waiting time). In the existing process, the aggregate is called and requested only when the planning process has started, which puts the paving process on hold for about 2 hours until the material is delivered even though the road has been prepared for laying of asphalt (i.e. the road is planed, swept and sprayed). There is an opportunity for process improvement, as presented by applying lean concepts, and eliminate the identified waste by shifting ahead the start time of the paver. To do so, the request of material delivery has to be done before the start of planning process. The processing duration of paver is relatively short considering the work window of the shift. Another opportunity for improvement is presented in extending the operation time of the paver, which means requesting material early and more planed, swept and sprayed surfaces.

Figure A13 shows the simulation model of the improved state. Key improvements involved ordering of material before the start of on-site activities. Because of increase in shift size and early commencement of pavement operations, the overall paver utilisation reached up to 67 per cent.

To validate a simulation model, two categories of data are required. First, there is need to collect robust and detailed data from the job site. Second, for validation purpose, empirical data on production rates and machine utilisation rates are required, to allow for a comparison with the model output. The output created by a DES simulation model consists of results mimicking the physical project for the model to be validated. Both categories of data came from various sources, including the company's sheets, reports and site observations. Also, some scenarios were simulated to validate the model, and they produced the following results:

5.1.1 Scenario No. 1: creating zones within the job site and increasing the number of planners and pavers. The first scenario assumed dividing the job site into two equal zones, Zones A & B, as shown in Figure A14. Each zone had its planners, one for each lane, while maintaining two lanes closed for resurfacing and two lanes open to public traffic. Both zones shared two pavers, five sweepers/pitch-sprayers and four rollers. In the same time, the scenario maintained the same work window. The key expected outcome was increased production in laid asphalt.

The simulation output is presented in Table III, with the total production rate increased up to two times (i.e. 276.9 tonnes/hour) the normal production rate. The simulation shows that the utilisation of pavers through the work window remains the same despite added machinery with an average utilisation rate of 65.3 per cent. As a result, an increment in the total production and production rate was expected, and the outcomes of the simulation met these expectations. Even though the production output increased, the added cost of extra machines should also be taken into account.

Table III. Results of Scenario No. 1

Scenario 1: Using two pavers and closing two lanes together			
Paver total output	Paver Avg. output	Paver 1 utilisation	Paver 2 utilisation
1,892 tonnes	276.9 tonnes/h	65.3%	65.3%

5.1.2 Scenario No. 2: providing a 30-min break from 2:00-2:30 a.m. This scenario focused on measuring the impact on production rates in the case of a 30-minute worker break from 2:00 a.m. to 2:30 a.m. Single paver operations were assumed. A 30-min break resulted in a decrease in the total production and production rate. The break decreased the total asphalt laid to 865 tonnes in comparison with the previous scenario of 1,892 tonnes' output. The production rate was recorded as 126.6 tonnes per hour. The utilisation of the paver through the work window shrank by 5.6 per cent. Thus, a 30-min break could lead to significant delays in larger projects. As a result, staggered break times are suggested, in which each team takes its break in a manner that does not affect the flow of work (Table IV).

5.1.3 Scenario No. 3: forecasting the time required to carry out a certain job. The third scenario assumed limiting motorway closures to a 6-km stretch. Two lanes were closed at a time for public traffic and 45-mm thick asphalt was to be overlaid. Each closure interval (two lanes) required one 1 extra hour to complete resurfacing of the closed lanes. The extra hour was required during the paving operation. Thus, additional investigation of the paving operation is required to accelerate the operation and reduce the required time by 1 hour instead of adding 1 h to it. Finally, resurfacing of the entire closure area required an hour to be added or eliminated from each shift (Table V).

6. Discussion

Literature review indicated that while there is an uptake of lean concepts and tools within the manufacturing, process and construction industries, there are very few examples and limited use of value stream mapping and process simulation within road transportation context. There is a need for integrated approaches that allow for a comparison between the performances of such practices in the existing systems (Detty and Yingling, 2000). An integrated VSM-DES framework based on the literature review presented a systematic description of how future VSM can be validated before implementation to achieve success. McDonald *et al.* (2002) explained how the integration might be able to predict the outcomes of dynamic situations that VSM alone is not capable of addressing. Once the current state is mapped, the workflow splits into two paths where DES and VSM are conducted in parallel.

By implementing a similar framework in the highway sector, critical paths and value stream maps can be visualised, validated and amended with changes in factors. Simulation can be performed at a micro and a macro level in resurfacing operation. For instance, it can map a truck travelling from an asphalt quarry to the work site and experiment various situations when this truck is delayed or broken down. In the same way, an end-to-end process can be drawn of any similar activity e.g. earthworks, traffic management etc.

This study dealt with the complicity of adopting lean concepts and process simulation technology for driving changes in the construction industry. A systematic approach was

Table IV. Results of Scenario No. 2

Break from 2:00 to 2:30 a.m.		
Paver total output	Paver Avg. output	Paver utilisation
865 tonnes	126.6 tonnes/h	59.7%

Table V. Results of Scenario No. 3

Scenario 3: Closing two lanes at once			
Paver total output	Paver Avg. output	Paver 1 utilisation	Paver 2 utilisation
1,892 tonnes	276.9 tonnes/h	65.3%	65.3%

presented for the application of lean construction concepts and tools to computer simulation models for increasing road surfacing productivity. These improvements were tangible, i.e. the waste (waiting time) as well as other non-value-adding activities were noticeably eliminated or reduced. The hourly production rate, resource (paver) utilisation and project duration were improved dramatically as a result of implementing lean concepts and tools.

In terms of the simulation, the numbers and rates shown in the model's output confirmed the validity of the models, thus opening up opportunities for producing a template model that includes deeper and more detailed factors that could affect the entire process, such as distance between job site and asphalt plant, failure of machines, delays caused by work accidents, severe weather conditions and delivered material failing under initial inspection. Further site observations and a detailed collection of data are required to build a further realistic model.

Material delivery time is also linked to the working style of the team on site. One of the major causes of delay in everyday work was that after the start of traffic management started and arrival of the team on site, material was called in as the last step. It then took time for the material to arrive on site. In the improved process shown in Figure A5, material was called in before the traffic management was started, giving enough time for it to arrive.

It was noticed during data collection and analysis that the road surfacing contractor only used the paving machine for 2 h of the 8-h work window allowed. This decreased the efficiency of the paver to 25 per cent which was a pure waste of resources. However, after improving the process, the efficiency reached up to 75 per cent. Road users are one of the most important stakeholders that will benefit from the positive implications of this study. Private resurfacing companies and transport departments can optimise their overall process and style of working by comparing their end-to-end processes and work plans with the ones mentioned in this paper. It will boost the productivity of equipment like planners and pavers and other machines used for resurfacing operations.

7. Conclusion

The purpose of this study was to investigate the relationship between DES and VSM and then apply it in highway operations to increase production rates and minimise road closures. Different scenarios were considered in the simulation to optimise the process. The best practice can be chosen after validating it through focus group discussions, workshops, etc. The case study results showed that just changing the working style can give huge benefits.

Although resurfacing and repairing of roads are inevitable, they can be optimised to an extent that general public is not disturbed by such operations. It is a well-accepted fact that stakeholders such as "motorists" are usually displeased about the continuous roadworks. There is scope for improvement in this regard by drawing upon the implications of "creation of zones" discussed in Scenario No. 1. (Figure A14).

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Appendix

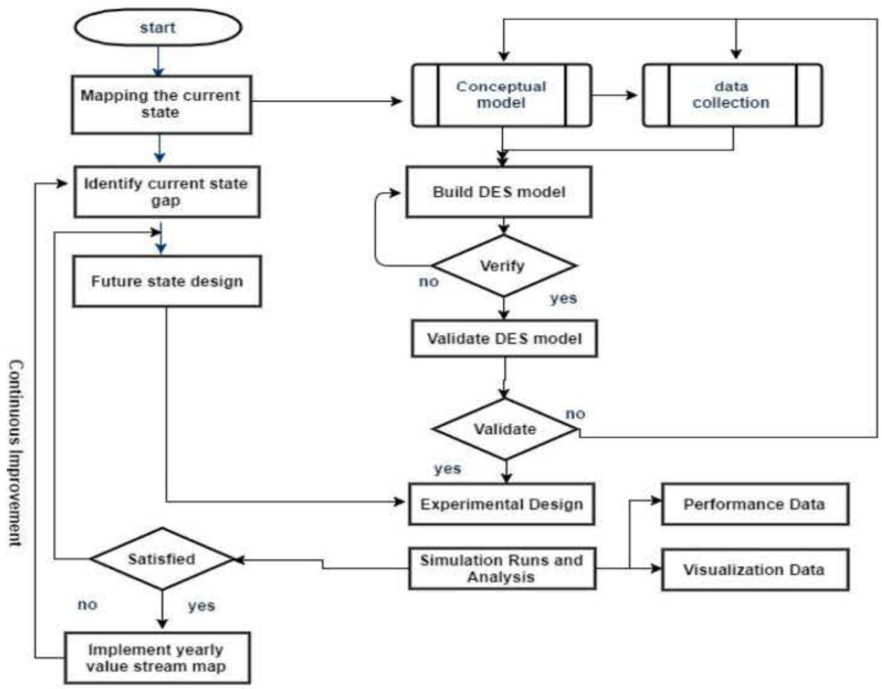


Figure A1.
DES-VSM integrated framework

Source: McDonald *et al*. (2002)

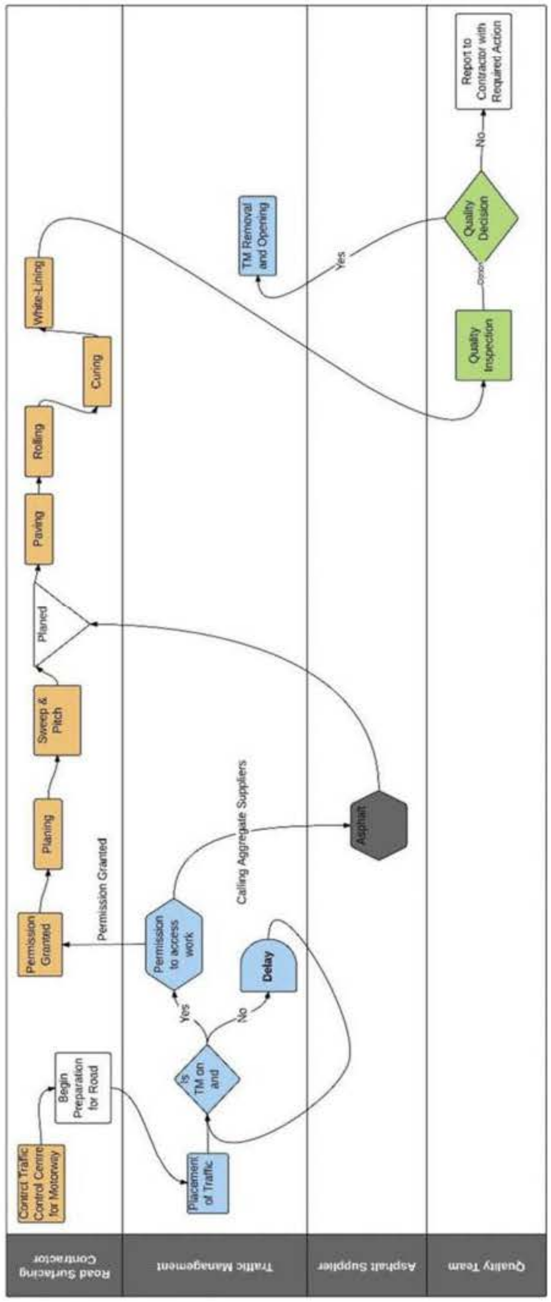
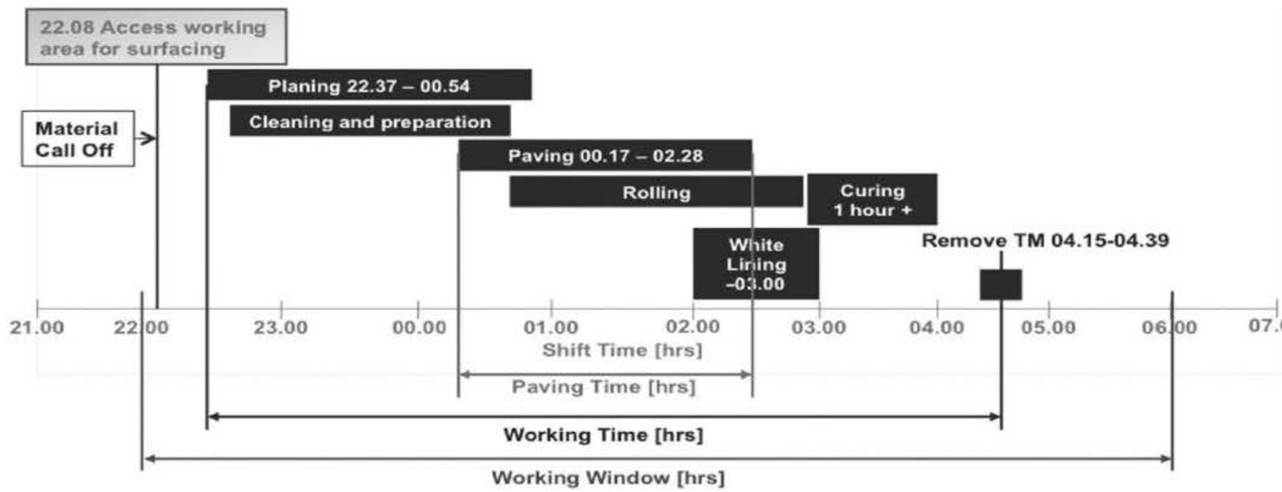
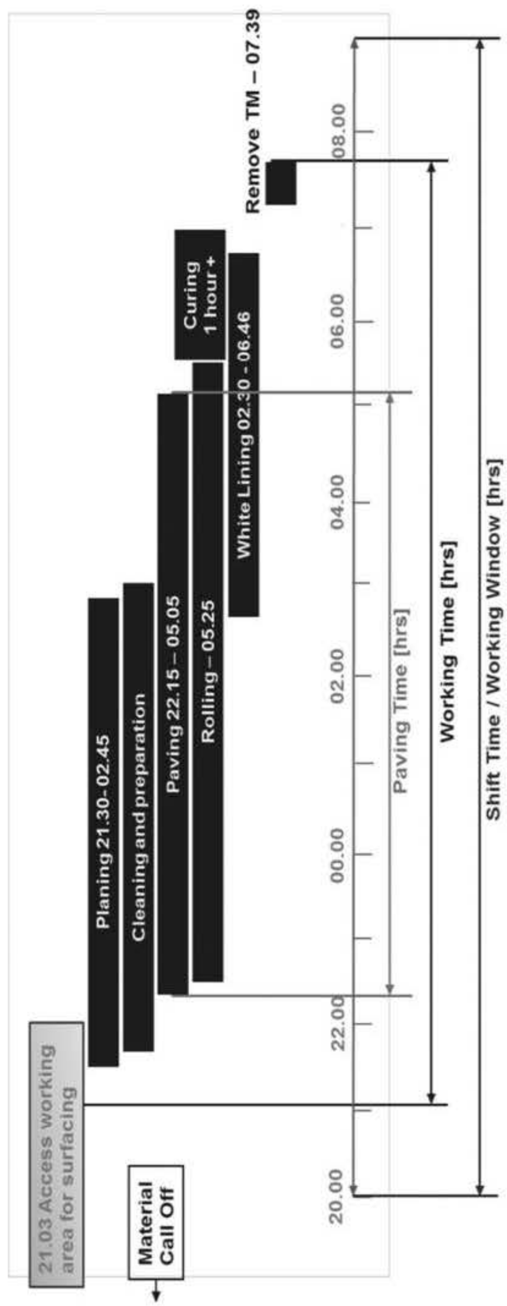


Figure A2.
As-is road pavement
surfacing



Source: Moore (2015)

Figure A4.
Road resurfacing operation, "as-is process"



Source: Moore (2015)

Figure A5.
Road resurfacing operation, improved process

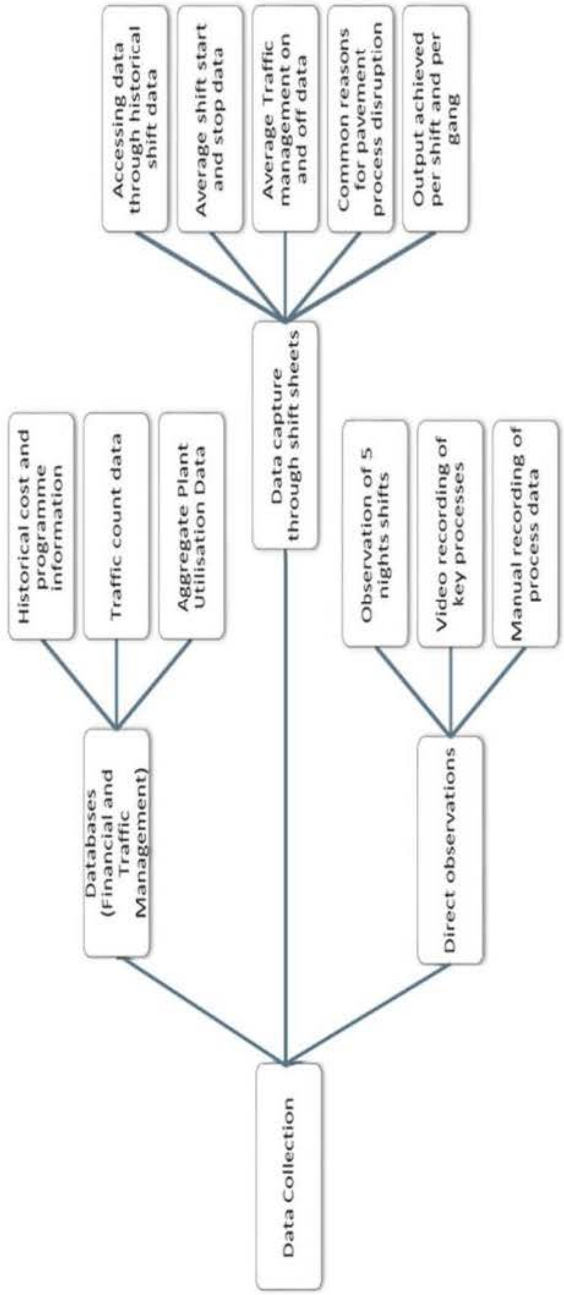


Figure A6.
Data collection methods

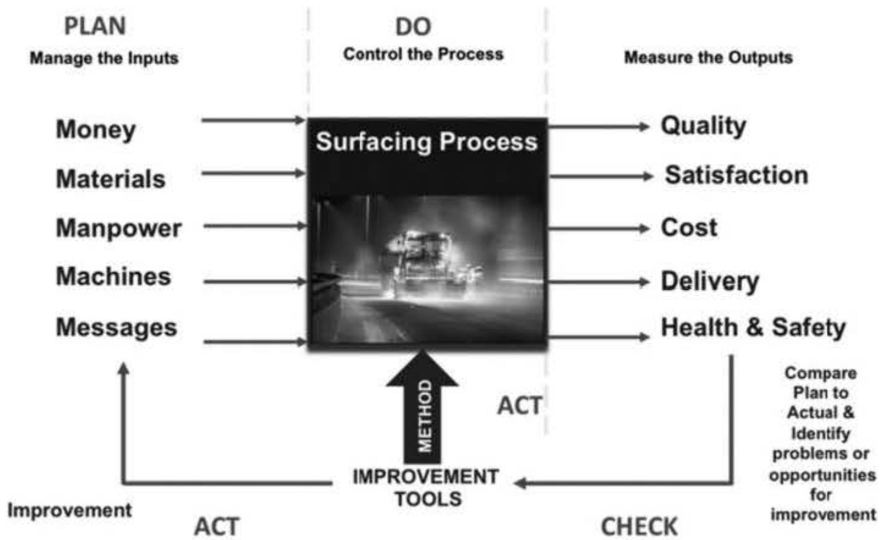


Figure A7.
Road surfacing process model

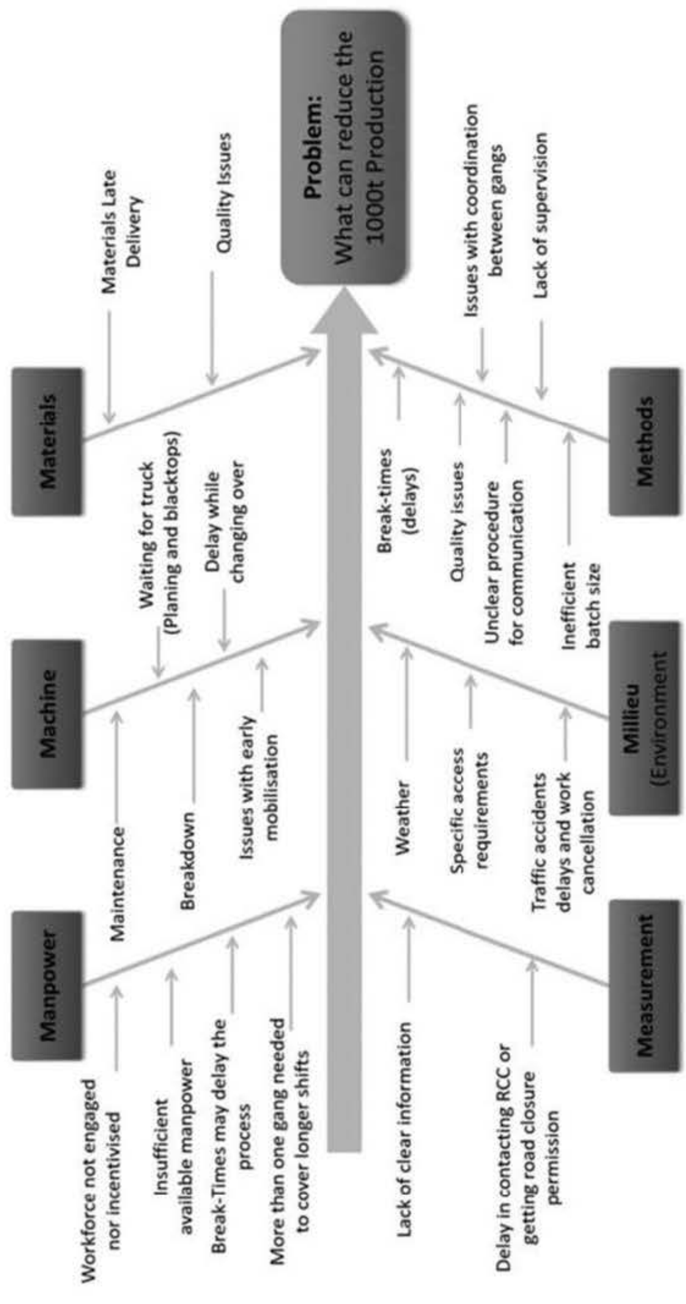


Figure A8.
Root cause analysis

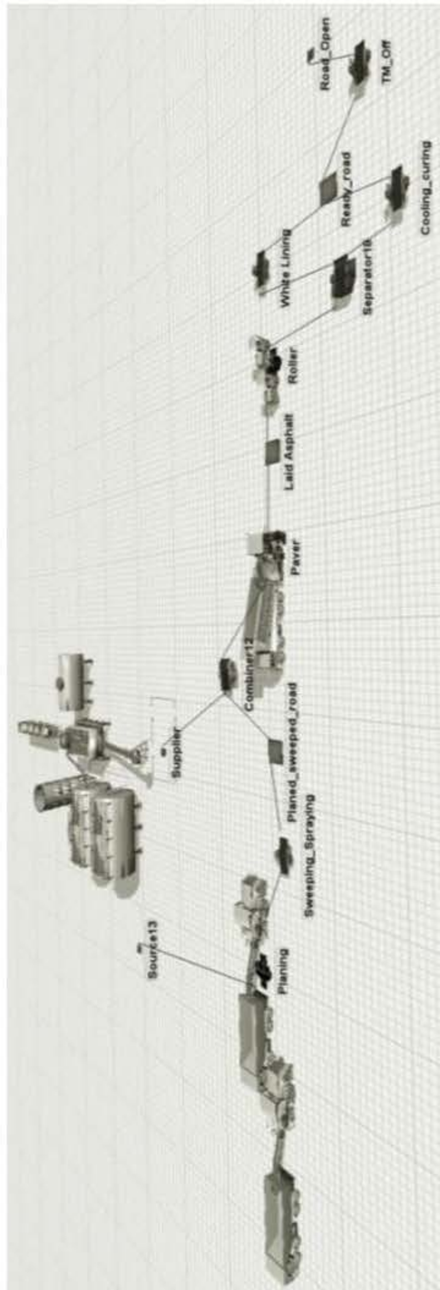


Figure A9.
FlexSim model representation of "as-is" state of road resurfacing (software used FlexSim)

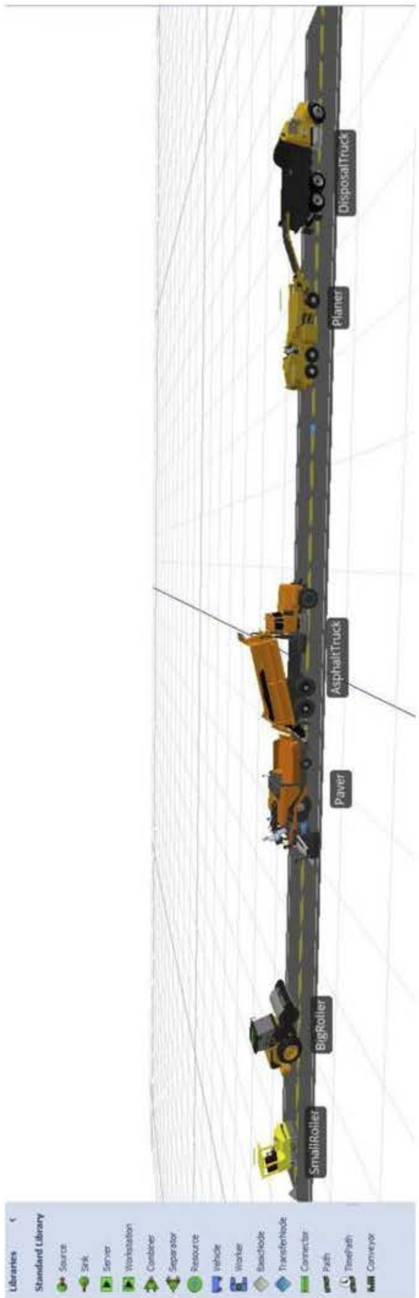


Figure A10.
3D presentation of asphalt machinery (software used: Simio)

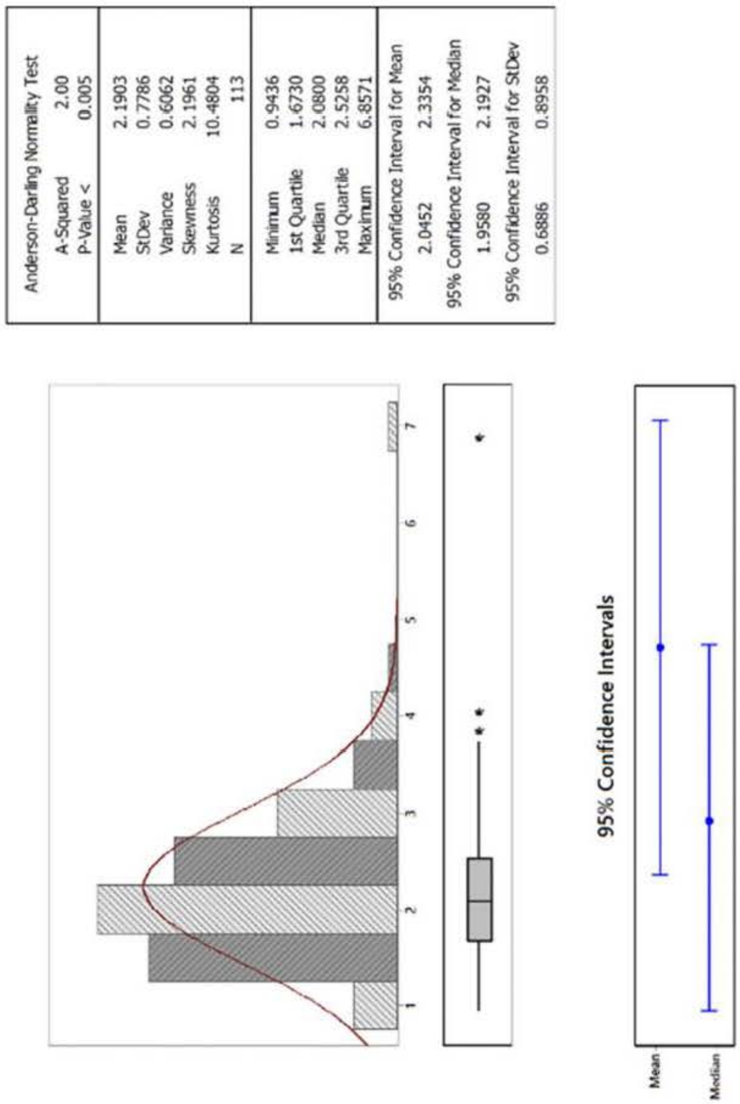


Figure A11.
Summary of paving rates (tonnes/min)

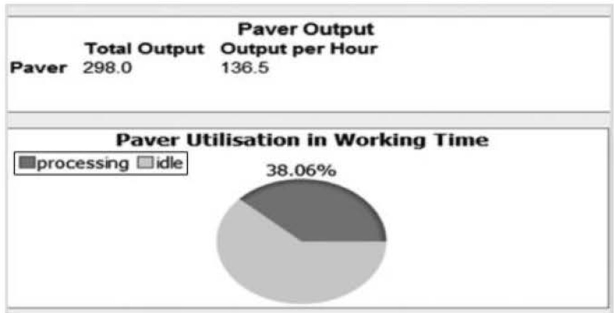


Figure A12. Discrete event simulation output of the as-is process (*FlexSim*)

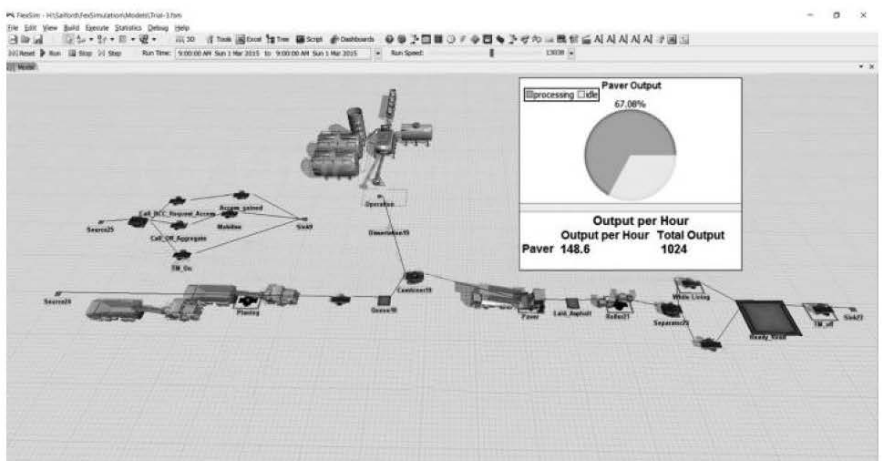


Figure A13. Future state after eliminating the "waiting time" waste from the process

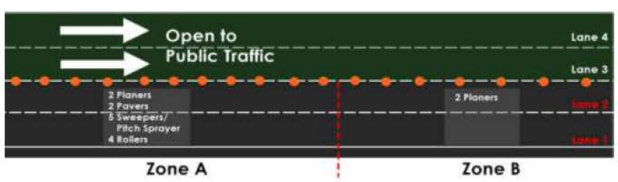


Figure A14. Scenario No.1 zoning plan

Corresponding author
Rana Muhammad Qasim can be contacted at: m.qasim1@edu.salford.ac.uk

Appendix 5: Conference Paper

The Ninth International Conference on Construction in the 21st Century (CITC-9)
"Revolutionizing the Architecture, Engineering and Construction Industry through Leadership, Collaboration and Technology" March 5th-7th, 2017, Dubai, United Arab Emirates

Improving Productivity of Road Surfacing operations with the help of Lean and Discrete Event Simulation techniques; a UK case study.

Rana Muhammad Qasim,
School of Built Environment, *University of Salford, Manchester, England, UK*
m.qasim1@edu.salford.ac.uk

Dr. Zeeshan Aziz,
School of Built Environment, *University of Salford, Manchester, England, UK*
Z.Aziz@salford.ac.uk

Abstract

Road surfacing is an important module in Highways Development and Maintenance sector. The resurfacing and rehabilitation of road pavements has become a costly requirement due to large number of private and commercial vehicles using the roads that cause pavements to disintegrate rapidly. The roadworks incur not only direct work costs, but also indirect costs from factors such as congestion, motor accidents, traffic disturbance and pollution. Maintenance activities on the roads usually cause delays and queuing. There is obviously a need for quick and cost effective maintenance that minimizes the occurrences and duration of these disruptions. This research investigates the role of Discrete Event Simulation (DES) to enhance the productivity of the delivery of road surfacing operations through achieving higher production rates and minimum road closure times.

Keywords

Paving, Process Improvement, Productivity, Resurfacing, Discrete Event Simulation

1. Introduction

Road surfacing is a critical component in Highways Development and Maintenance all over the world. In England, Office of National Statistics (2013) claimed that in the first quarter of 2015, the output of road works, as part of infrastructure works, reached up to £1,115 million. New infrastructure and congestion relief projects can be delayed and are usually delayed due to various reasons, mainly financial problems. However, maintenance (resurfacing, rehabilitation etc.) projects cannot be deferred as they directly affect the road network. As soon as a road is built, it starts deteriorating due to many causes like weather, traffic and quality of materials (Department for Transport, 2013). It is a common phenomenon worldwide and its timely mitigation is necessary. Even in a developed country like USA, 32% of roads are in poor or mediocre condition and motorists are paying $67 billion a year in repairs and operating costs (ASCE, 2013). Without appropriate rehabilitation, these structures will eventually collapse causing even bigger challenge for traffic (Christory et al., 2008). Road surfacing process is carried out every night throughout the year in almost every country around the globe. There can be differences in terms of timing, contract types and techniques used, however, the machinery and task is similar everywhere and what really need to change is the working style itself. Furthermore, there is an urgent need for improving the productivity of road works projects within the construction industry to deliver ongoing and future projects with the maximum efficiency and minimum waste

Highways context is very unique when compared to other industries like manufacturing or processing because of its fragmented nature which requires more in depth approach (Dutta et al., 1993; National Research Council 1994). This business consists of various engineering companies, contractors, suppliers, and equipment manufacturers and equipment providers (BIS, 2013). Since different stakeholders are involved in the construction and maintenance of highways at different tier levels, numerous improvement schemes are frequently overlooked due to deficiency of consensus between stakeholders. This was also acknowledged by the Office of the Parliamentary Counsel, (2013) that having more stakeholders in any project makes it complex and the improvement schemes are often ignored. However, if there is an improvement scheme with firm evidence e.g. a computer based simulation model, which manages to take all stakeholders on board, there is less room for rejection.

This paper looks in to current practices of pavement in United Kingdom and then strives to improve the productivity of overall process by 1) using discrete event simulation to find the most efficient methods by performing various what-if scenarios and 2) by improving traditional mapping techniques e.g. value stream mapping with the help of simulation techniques. This paper is further divided in to sections including relationship between lean and DES, case study work, simulation model design, discussion and conclusions.

2. Value Stream Mapping (VSM), a Lean tool and Discrete Event Simulation (DES)

The implementation of simulation techniques in highways context is limited and only a handful of studies have been done to advance the process e.g. by (Maji & Jha, 2009; M Marzouk et al., 2011; Jones 2011). Existing optimisation approaches rely heavily on manual process methods like Process Activity Mapping, Quality Filter Mapping, Decision Point Analysis and Value Stream Mapping. VSM was derived from Toyota production and Lean manufacturing philosophies (Womack et al., 1990). It is defined as a repetitive method to map and analyse value streams to evaluate and connect production process aspects like information and material flows plus other non-value adding actions (Rother and Shook 2003; Lasa et al., 2008).

It is used in improvements schemes like increasing throughput and for reduction of lead time and work in progress (Álvarez et al., 2009). VSM, however, cannot provide hard facts for decision making and simply points toward a direction. It cannot help to forecast analytically the effects on upcoming performance of a system, hence the need of Simulation arises to experiment and evaluate the future behaviour of a scheme (Jarkko et al., 2013). VSM is used frequently in Highways sector, especially Highways England at various levels and processes, which makes it important to optimise it by eliminating its deficiencies to achieve the purpose of this research. Discrete Event Simulation (DES) along with Value Stream Mapping (VSM) has been recognised as a technique that can improve the overall process as well as some specific key areas. The deficiencies in VSM can be reduced by combining it with DES and it has been experimented well in different industries. Literature indicates that manufacturing (Marvel and Standridge, 2009), process (Abdulmalek and Rajgopal, 2007), construction (Jarkko et al., 2013) and healthcare sectors (Xie and Qingjin Peng, 2012) have improved their processes and benefitted from simulation, value stream mapping and the integration of both. Simulation has been trialled in Highways process by (Marzouk et al., 2011), however, it only focussed on a very particular activity (effect of maintenance activities on traffic).

Literature review indicates the use of different approaches to describe productivity. Despite the use of different techniques, the fundamental concepts remain the same. Rebholz, Al-Kaisy, & Nassar (2004) defined productivity in road construction industry as the quantity of laid asphalt in tonnes per hour or per day was adopted. For purposes of this research, this definition was adopted.

3. Case Study work

This section presents a detailed case study of a road surfacing process improvement project at the project level, involving usage of lean tools alongside Discrete Event Simulation to explore opportunities of optimising existing road surfacing process. All types of road work processes, whether new constructions or maintenance work, are classified into two major types i.e. surfacing and resurfacing. Every road surface has its diverse characteristics, which vary according to its geography, location, surrounding terrain, speed related parameters, intended use, and type of pavement. To optimise the current resurfacing operations in UK, Highways England trialled a lean experiment to identify the wastage in the process and improve it using lean methods. The motivation was to deliver efficiency by maximised output and use of resources, improved utilisation of road space and benefit the travellers through less road closures. There were inefficiencies noticed in the process and due to incompetent working style of subcontractors, huge amount of resources were wasted and traffic was disrupted on daily basis.

After studying the process in detail for a few days, it was noticed that key constraints that must be addressed before start of pavement process were setting up of Traffic Management (typically 15 minutes), material call-off and planer mobilisation (typically 30 minutes), and planning a head start (typically 45 minutes), leading to a total non-value adding the pre-paving time of 1 Hr 30 minutes. Key post-pavement process constraints include rolling (typically 30 minutes), cooling and curing (typically 75 minutes) and Traffic Management removal (typically 30 minutes). This means a total of 2 hours and 15 min post is paving shift period. A safety margin of around 1 Hr 30 Mins is left for safety related activities. Installation and removal of Traffic Management has an average duration between 30 minutes to 45 minutes and depend on a wide range of variables including use of different designs and types of TM, delays and operator/process related variables.

In this particular case, to improve the process and minimise the wastage between motorway closure and planing operation, several opportunities were recognized. The work plan was divided into three major steps. Initially, by allowing an early contact between local traffic control centres, the process was expedited and waiting time for clearance process was shortened. It was noticed that material was called off after the operation starts every night and while the material travels from quarry to work site, workforce was sitting idle. Secondly, traffic management was set out to close two lanes earlier and bring plant and material ahead of full closure (safety constraints were addressed). This assured that plant and material are accessible ahead of full road closure. In order to boost the productivity of pavement process, calling material earlier would allow paver to begin operations early. There is a time lag of 14 minutes involved between planer and paver processes to commence, to allow time for cleaning and preparation. (Moore 2015) The third step was to ensure that work continues close to 6 am – the allocated work window rather than 4:30 am (traditional time). Given the fact that paver utilisation in an average shift is just 33%, doubling pavement productivity by addressing constraints (E.g. earlier mobilisation of paver, full utilisation of work window) has the potential to double paver productivity and thus, the output produced. According to Moore 2015, the possibility of extending work windows particularly over weekends or public holidays, when lesser than average traffic volumes are accepted, provided an opportunity to increase working window, which had a direct positive correlation with productivity. It involved increasing work window to 10 hours and 36 minutes.

Table: 1 Showing Various Improvements in baseline process using lean. (Adapted from Moore 2015)

Activities	Baseline Process	Improved Process
Shift Duration	**10 hours**	**10 hours (staggered)**
Working Window (Theoretical)	**8 hours (22:00 – 06:00)**	13 hours (20:00 to 9:00 am)
Working Window (Actual)	**6 Hr 31 Mins (22:08-04:39)**	10 hours 36 minutes (21:03 – 7:39)
Tonnage Laid	298 T	**1024 Ton**
Paving Duration	2 Hr 11 Min	**6 hour 50 minutes (22:15 – 5:05am)**
Average hourly tonnage laid	137 T (@45 mm thin surfacing)	149 T (@45mm thin surfacing)
Pavement length laid (in meters)	938 m	2700 metres
Paver Productivity	33 % (2Hr 11 Min / 6Hr 31 Min)	**64 % (6hr 50 min / 10 hours 36 mins)**

4. Simulation Model Design

The definition of the simulation scope is crucial for defining the analysis boundaries. Clearly defined scope of simulation system and boundaries could result in more useful simulation. The scope of simulation development in this study is limited to all activities involved from road surfacing activity start (i.e. from the time of road closure for surfacing purpose) till the road is open again. After defining the boundaries, it is important to identify key assumptions of how the system being studied, act together with its defined external environment (Beaverstock, Greenwood, & Nordgren, 2014). Preparation and logistic activities were included in the model, taken as fixed timings as measured on site, and are not part of the analysis. The simulated operation activities included planing, sweeping and pitch spraying, paving, rolling, white-lining, and testing. Any sub-activities within each one of these activities is not considered. All required material in the process is assumed to be always available and delivered on time. Downtime of equipment is not included in the simulation. Also, the Simulation is based on paving 45mm thick surface course.

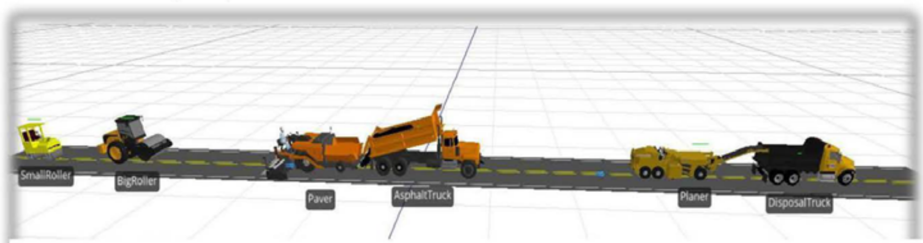


Figure 1 showing the 3d model of asphalt machinery in operation. (Software used Simio)

In modelling the random elements within the road surfacing process, it is important to replace time certain components with a probability distribution. Three randomly distributed components are used: asphalt inter-arrival delivery, asphalt truck position time, and paving times. To determine the probability distributions that are used to model the resurfacing process, historical data collected over 115-night shifts over a six months period was used. To select the suitable Probability Distribution, the historical data collected from 115-night shifts was analysed and tested against Anderson-Darling normality, using a statistical distribution software application (i.e. *Minitab 17)*. Since the paving process constitutes a major operation, other subsidiary processes e.g. planing were assumed to match the production rate of the paver. However, detailed analysis of data indicate the average time for planing is 2.17 tonne/minute, and for paving it is 2.19 tonne/minute (Figure 2).

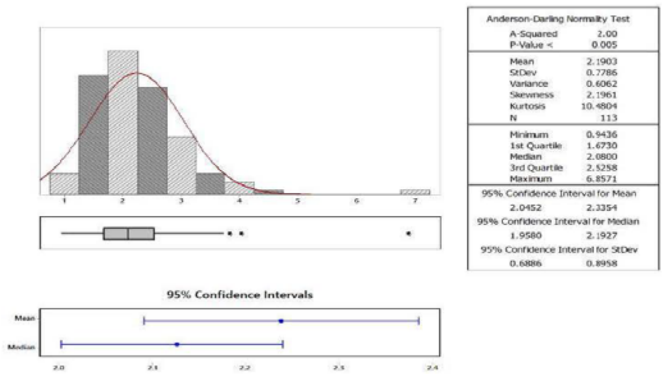


Figure 2 Summary for Paving Rates (Tonnes/min)

The following calculations were done to have unified units to be used in *FlexSim:* Assuming process flow-item equals one (1) tonne of asphalt. For Paving, the average paving rate is 2.19 tonne/min i.e. 131.4 tonne/hr, which means that (1) tonne requires 27.40 sec to be paved.

4.1. Simulation outputs and Validation

With a small difference in values, the simulation outputs came as a confirmation of the need to improve the current state as the percentages of paver utilisation is considered to be low compared to the permissible working window of the shift. The paver is working only for thirty-eight percent (38%) of the time starting from road closure until the road is open again (Table 2). These outputs and percentages provide a credible evidence of the waste existence in the process of road surfacing. It can be concluded that the major waste in the process is in the form of "waiting" for the paver to start processing.

Table: 2 showing Discrete Event Simulation Output of the based on as-is process

As-is Process Simulation		
Output per hour	**Total Output**	**Paver utilization in working time**
136.5 Ton	298 Ton	38.06%

Figure 3 below illustrates simulation model of the improved state. Key improvements involved an order of material before the start of on-site activities. Because of increased of shift size and early commencement of pavement operations, overall paver utilisation has reached up to 67%.

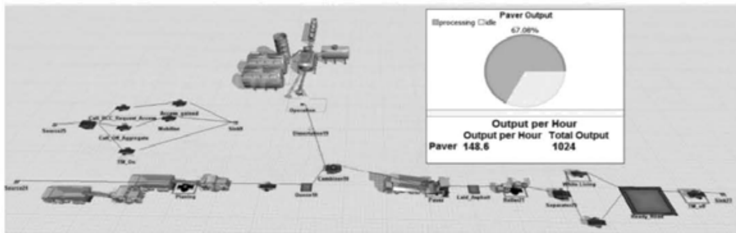


Figure 3 Future-State after Eliminating the "waiting" Waste from the Process

To validate a simulation model, there are two required categories of data. Firstly, there is need to collect robust and detailed data from the job site. Secondly, for validation purpose, empirical data on production rates and machine utilisation rates are required, to allow for a comparison with the model output. The output created by a DES simulation model consists of results mimicking the physical project for the model to be validated. Both categories of data came from various sources including, company's sheets, reports, site observations. Also, some scenarios were simulated to validate the model and they produced the following results:

Table: 3 showing Various what-if Simulated scenerios and their effect on output

Paver Total Output (Tons)	Paver Average Output (Tons/hour)	Paver Utilization (%)
Scenario 1: Using Two pavers and closing two lanes together		
1892	276.9	65.3% for each paver
Scenario 2: Providing a 30 min break from 2:00-2:30 am		
865	126.6	59.7
Scenario 3: Closing two lanes at once and using 2 Pavers		
1892	276.9	65.3 % for each paver
Scenario 4: Closing the Road for 55 hours (like California)		
15,954	358.4	71

5. Discussion & Conclusions

Although, there is an uptake of simulation concepts and tools within the construction industry; there are very few examples and limited use of it within road transportation context. There is alos a need for integrated approach that allow for a comparison between the performances of lean practices to the existing systems (Detty & Yingling, 2000). An Integrated Value Stream Map and Discrete Event Simulation Framework based on the review of literature presented a systematic description of how future VSM can be validated before implementation. McDonald, Aken, and Rentes (2002) explained how the integration might be able to predict the outcomes of dynamic situations that VSM is not capable of addressing alone. Once the current state is mapped, the workflow splits into two paths where DES and VSM are conducted in parallel. The flow diagram of the integrated framework is shown in Figure 4 below.

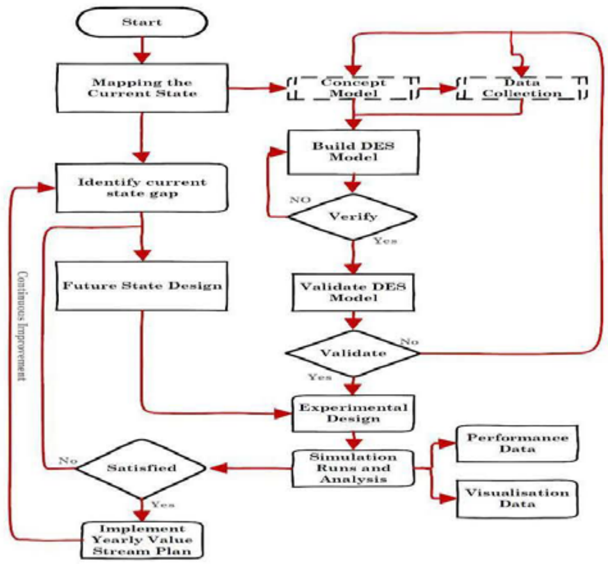


Figure 4 DES-VSM Integration Framework (McDonald, Van Aken, & Rentes, 2002)

This research dealt with the complicity of adopting Lean concepts and process simulation technology in changing the construction industry. It presented a systematic approach for the application of lean construction concepts and tools into computer simulation models. Moreover, research demonstrates how road surfacing productivity can be enhanced by applying lean concepts and tools. These improvements are tangible; noticing the waste (waiting) was eliminated or reduced as well as non-value added activities. The hourly production rate, resource (paver) utilisation, and project duration were improved dramatically, as a result of implementing Lean concepts and tools.

In terms of the simulation, the numbers and rates shown in models output confirm the validity of the built models which open opportunities of producing a template model that includes deeper and more detailed factors that could affect the entire process, such as distance between job site and asphalt plant; failure of machines; delays caused by work accidents, severe weather conditions; delivered Material is failing under initial inspection and more site observation and detailed collection of data are required in order to build a further realistic model.

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